Lattice QCD for the intensity frontier

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2012 Project X Physics Study
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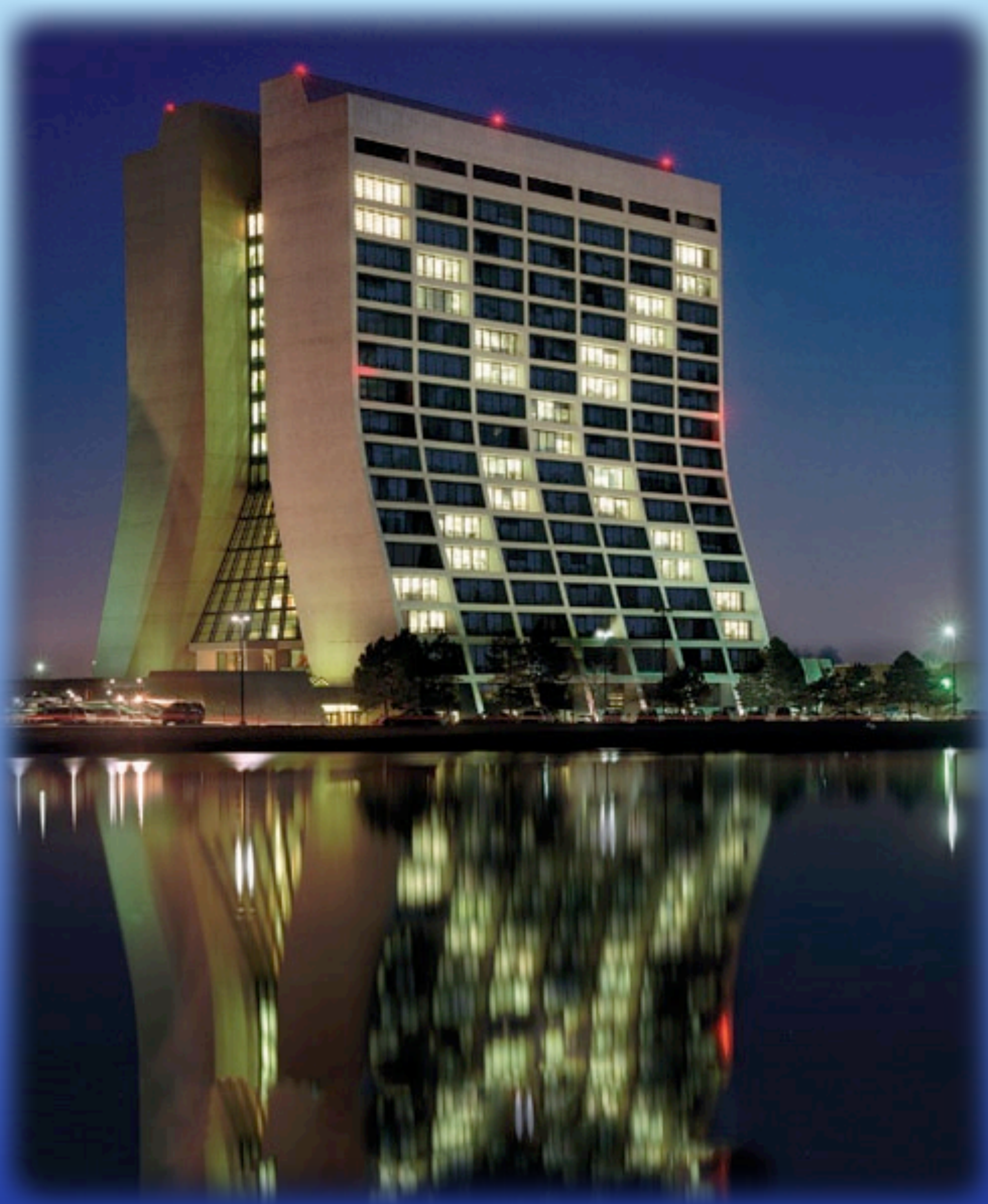


Beyond-the-Standard-Model search strategies

✦ The experimental high-energy physics community is presently searching for new physics with two complimentary approaches

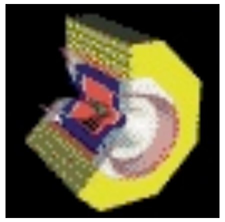
(1) Production of new particles at colliders

❖ *E.g.*, the LHC will either discover or rule out a Standard-Model Higgs by the end of this run

(2) Precise measurements of Standard Model parameters and processes

❖ *E.g.*, heavy-flavor factories have been pouring out data to pin down CKM matrix elements & the CP-violating phase and to measure decay rates for rare processes

❖ Look for inconsistencies and compare to beyond-the-Standard Model predictions



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Lattice-QCD calculations are needed to interpret many of their results . . .

❖ Look for inconsistencies and compare to beyond-the-Standard Model predictions

The intensity frontier

- Study fundamental physics with intense sources and sensitive detectors
  - Search for processes that are EXTREMELY RARE IN THE STANDARD MODEL
  - Look for tiny deviations from Standard-Model expectations

kaon physics

B & D physics

muon g-2

neutron EDM

neutron oscillation & decay

hadronic physics

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Broad range of measurements that can be addressed with the

Project X

accelerator complex

g-2

& decay

LANSCE
Los Alamos Neutron Science Center

SNS
SPALLATION NEUTRON SOURCE

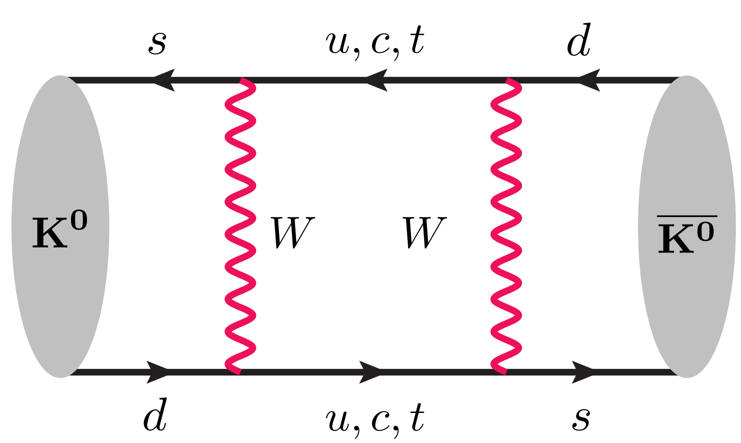
hadronic physics

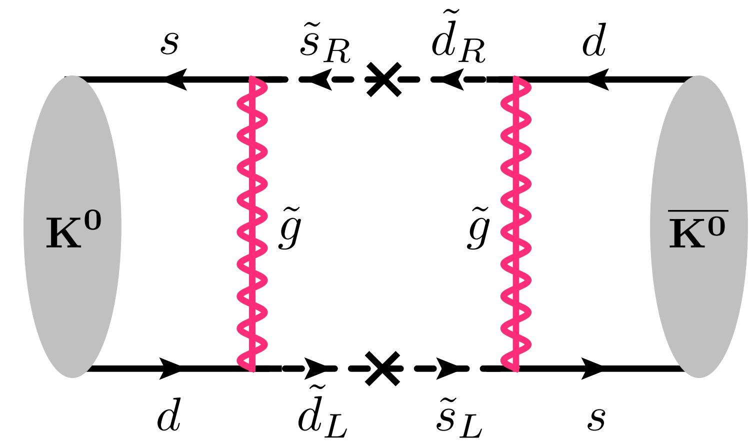
SeaQuest
E906

Why search at the intensity frontier?

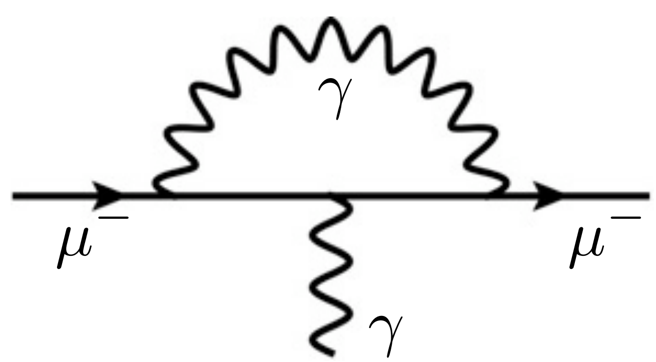
- Precision measurements probe quantum-mechanical loop effects, e.g.:

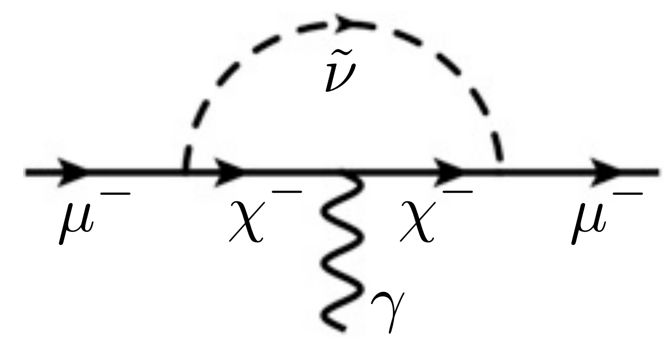
neutral kaon mixing





muon g-2



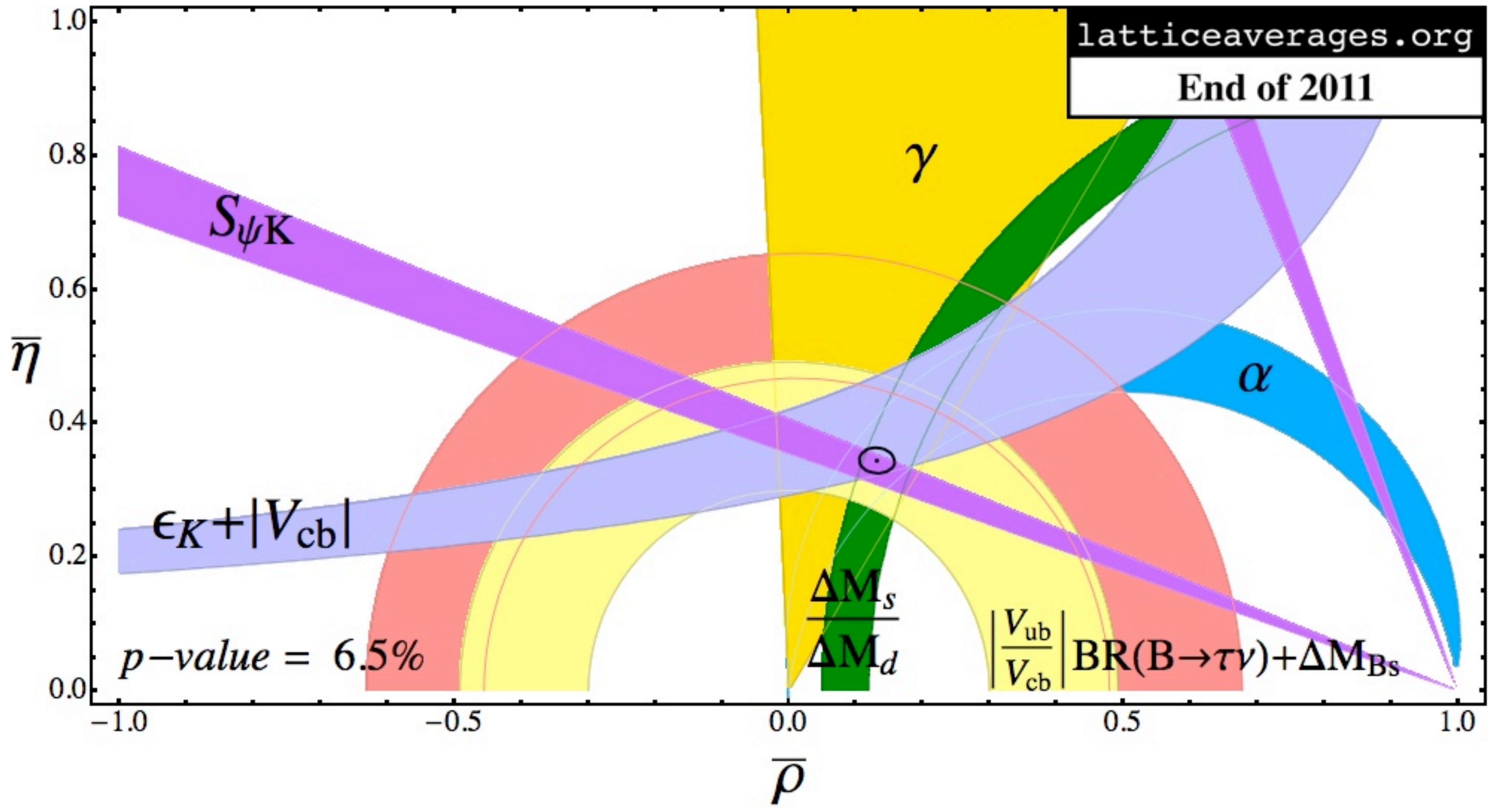


- Sensitive to physics at higher energy scales than those probed at LHC, in some cases O(1,000 - 10,000 TeV) [Isidori, Nir, Perez, Ann.Rev.Nucl.Part.Sci. 60 (2010) 355]

- If new particles are discovered at ATLAS & CMS, precise measurements will still be needed to extract the flavor & CPV couplings and determine the underlying structure of the theory

Why lattice QCD?

- **Comparison between measurements and Standard-Model predictions still limited in most cases by theoretical uncertainties**, often from hadronic matrix elements



Precise lattice-QCD calculations are crucial to maximize the scientific output of the future high-intensity physics program

Outline

1) Motivation
2) Introduction to lattice QCD
3) Select lattice-QCD results
   - Hadron spectrum
   - Standard-Model parameters: quark masses & α_S
   - *Predictions*
   - Flavor physics
4) Lattice QCD for Project X
5) Outlook

Introduction to lattice QCD

Quantum Chromodynamics

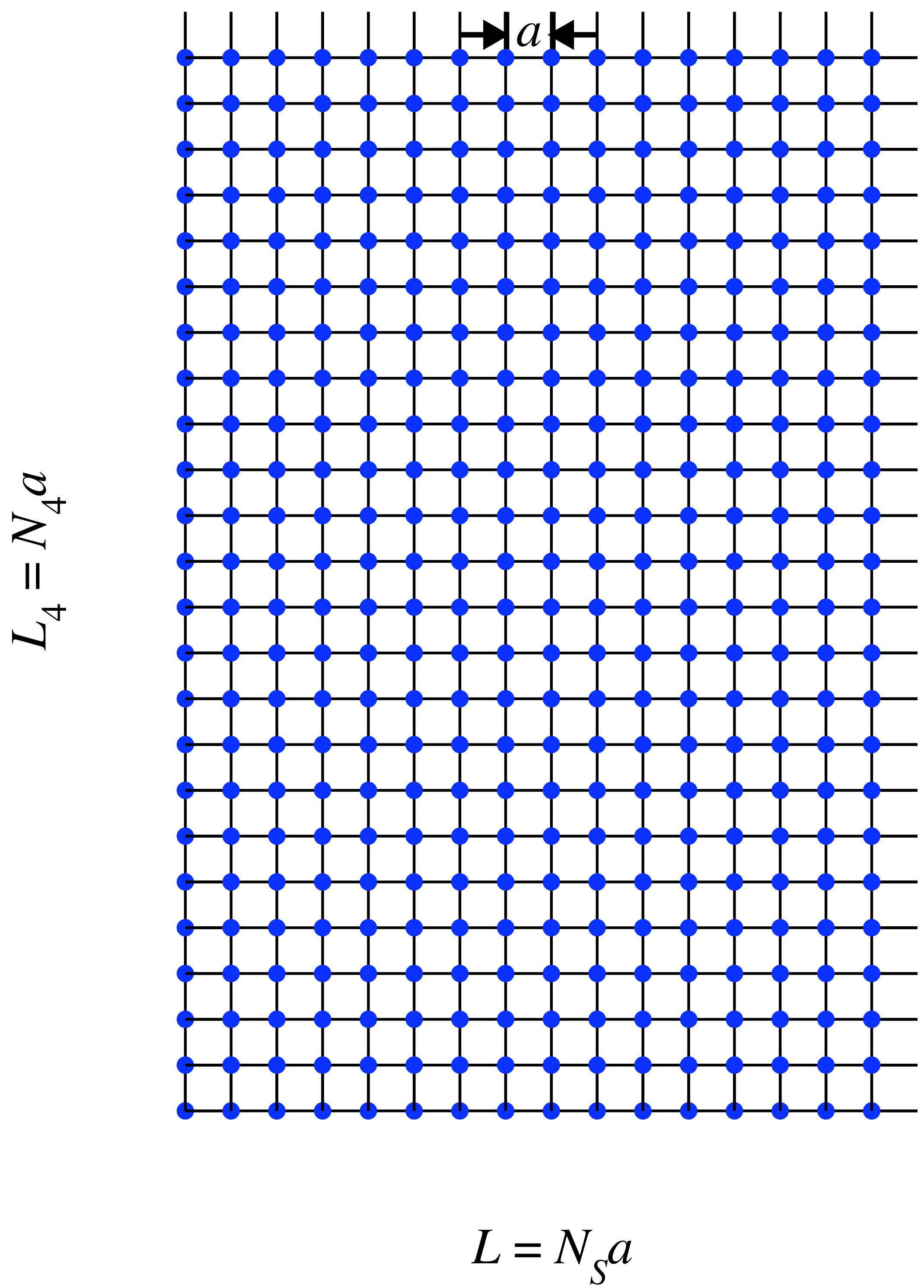
- QCD Lagrangian contains 1 + n_f + 1 parameters:

$$\mathcal{L}_{\rm QCD} = \frac{1}{2g^2}\mathrm{tr}\left[F_{\mu\nu}F^{\mu\nu}\right] - \sum_{f=1}^{n_f}\bar{\psi}_f\left(\not{D} + m_f\right)\psi_f + \underbrace{\frac{i\bar{\theta}}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\left[F_{\mu\nu}F_{\rho\sigma}\right]}_{\text{violates } CP}$$

- Gauge coupling g^2 — r_1, m_Ω, Υ(2S-1S), or f_π
- n_f quark masses m_f — m_π, m_K, $m_{J/\psi}$, m_Υ, …
- Experimental bound on $|\theta|<10^{-10}$ from neutron EDM — $\theta = 0$

- **Once the parameters of the QCD Lagrangian are fixed, everything else is a prediction of the theory**

Lattice Quantum Chromodynamics



- Systematic method for calculating hadronic parameters from QCD first principles
- Define QCD on a (Euclidean) spacetime lattice
- Replace derivatives by discrete differences and integrals by sums, *e.g.*:

$$\partial\psi(x) \longrightarrow \frac{\psi(x+a)-\psi(x-a)}{2a}$$

$$\psi(x) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot x}\tilde{\psi}(k) \longrightarrow \sum_k e^{-ik\cdot x}\tilde{\psi}(k)$$

- In the Feynman path integral:
  - Lattice spacing, a, provides UV cutoff
  - Box size, L, provides IR cutoff
- Recover continuum action when a→0, L→∞

Numerical Lattice Simulations

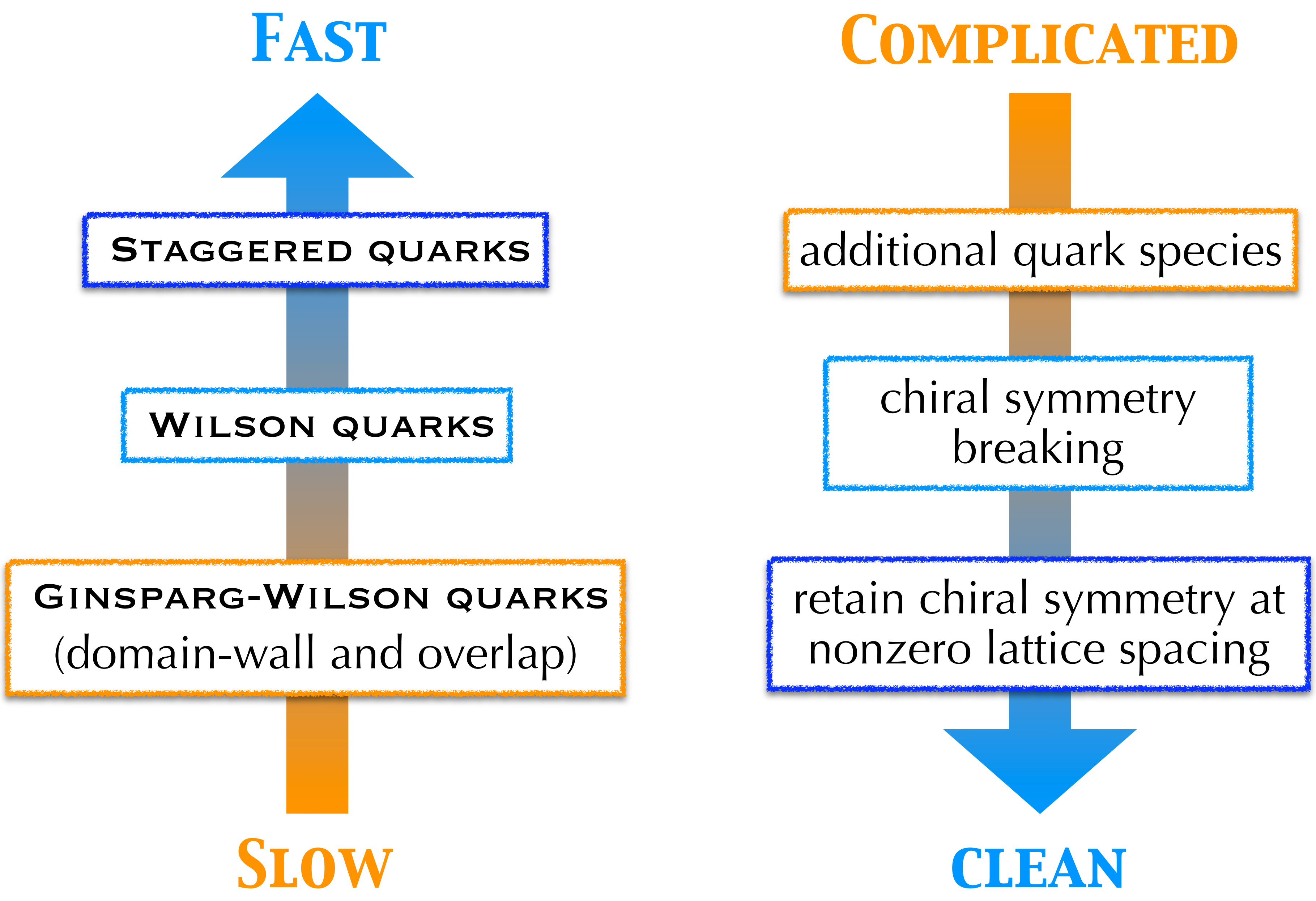
- Can simulate QCD numerically using **Monte Carlo methods**:
  - In quantum field theory, all field configurations are possible, but those near the classical (minimal) action are most likely
  - Lattice simulations sample from all possible field configurations using a distribution given by $\exp(-S_{QFT})$
- In practice extremely time consuming -- even on the fastest computers!

Fermilab lqcd clusters
~165 TFlops peak

Argonne BG/P
~557 TFlops peak

Lattice actions

✦ Different choices of action are optimal for different physical quantities

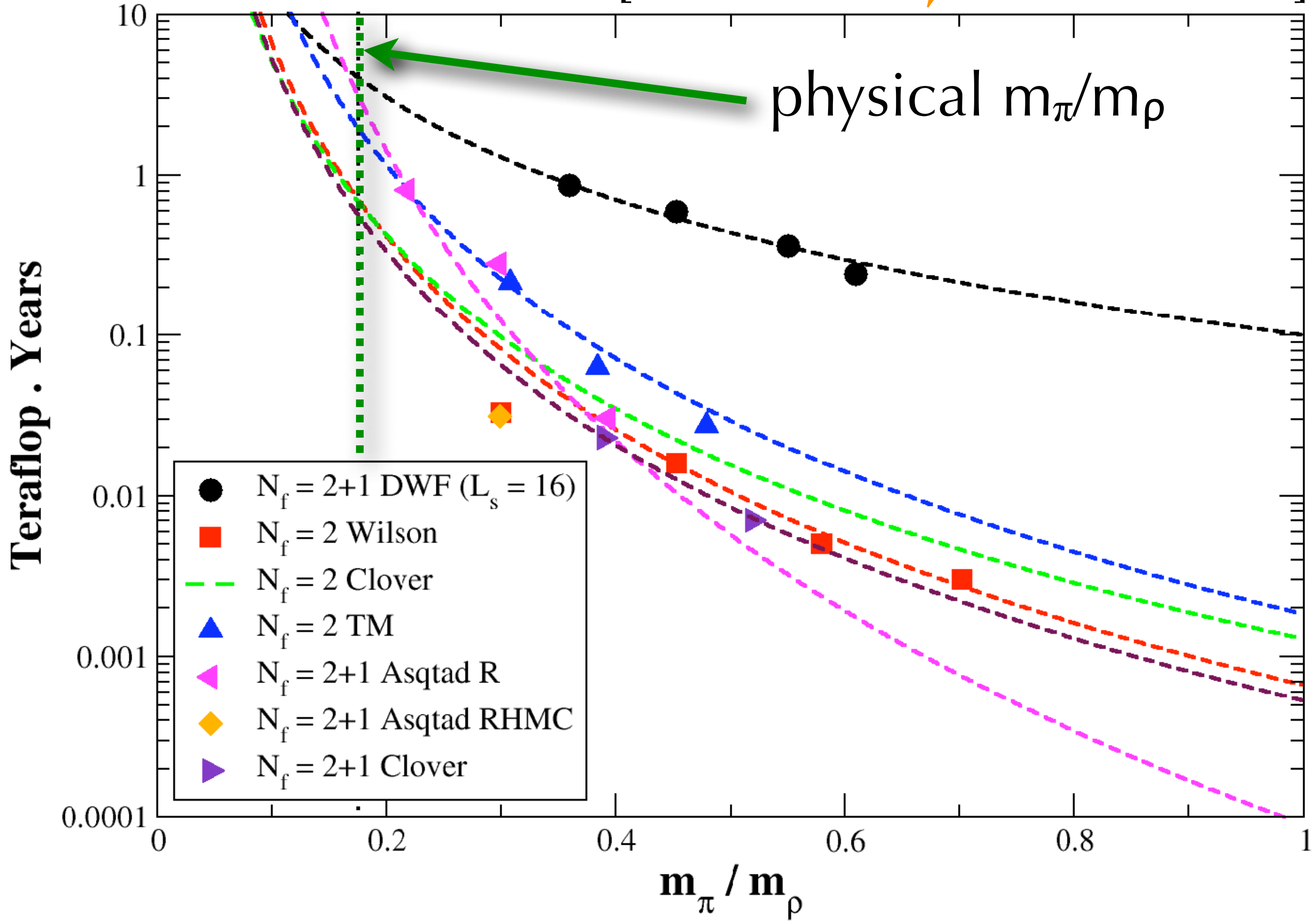


✦ All actions reduce to QCD in the continuum limit (a→0)

Lattice quark masses

- Time required for simulations increases as the quark mass decreases, so quark masses in lattice simulations are higher than those in the real world

[Mike Clark, Lattice 2006]



- Typical lattice calculations now use pions with masses $m_\pi < 300$ MeV
- State-of-the art calculations for some quantities use pions at or slightly below the physical mass $m_\pi \sim 140$ MeV

Improvements in algorithms and increased computing power will ultimately make a chiral extrapolation unnecessary

Lattice calculations

- Compute operator expectation values on an ensemble of gauge fields $[\mathcal{U}]$ with a distribution exp[-S_{QCD}]:

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \underbrace{\mathcal{DU}}_{\text{MC}} \, \underbrace{\mathcal{D}\psi_{\text{sea}} \mathcal{D}\bar{\psi}_{\text{sea}}}_{\text{by hand}} \, e^{-S_{\text{QCD}}[\mathcal{U},\psi_{\text{sea}},\bar{\psi}_{\text{sea}}]} \mathcal{O}[\mathcal{U},\psi_{\text{val}},\bar{\psi}_{\text{val}}]$$

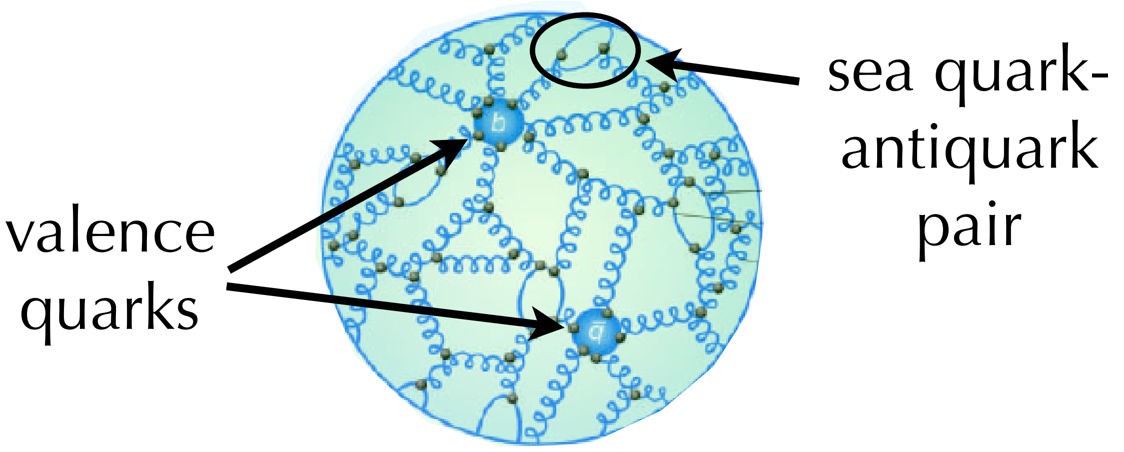
$$\downarrow$$

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{DU} \prod_{f=1}^{n_f} \det \left(\not{D} + m_f \right)_{\text{sea}} e^{-S_{\text{gauge}}[\mathcal{U}]} \mathcal{O}[\mathcal{U},\psi_{\text{val}},\bar{\psi}_{\text{val}}]$$

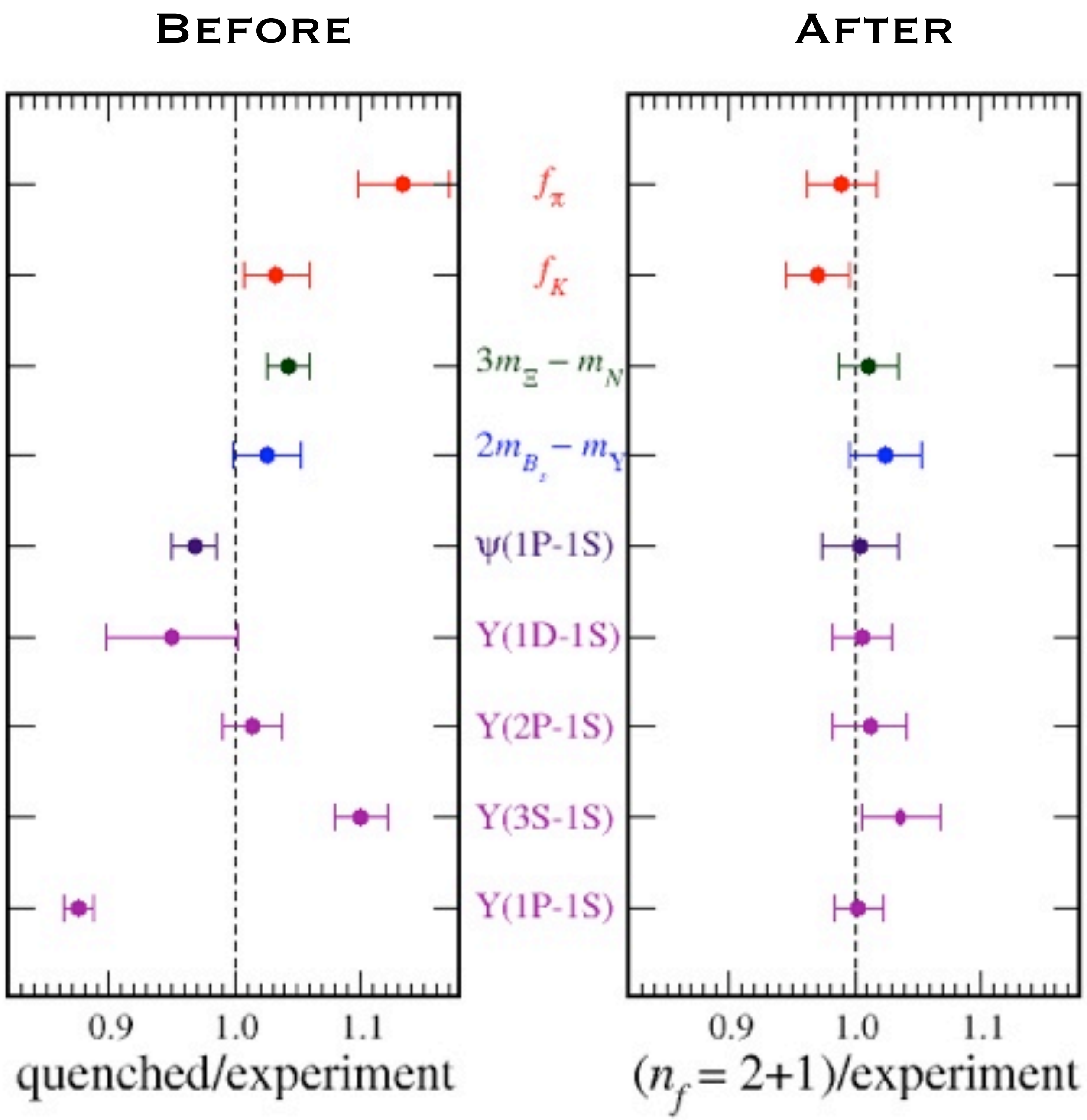
- **Quenched**: replace det→1 (uncontrolled "approximation" ⇒ don't do it!)
- **Partially-quenched**: let $m_{val} \neq m_{sea}$ (recover QCD when $m_{val} = m_{sea} = m_{phys}$)
- **Mixed-action**: let $D_{val} \neq D_{sea}$ (recover QCD when lattice spacing a→0)
- **n_f=2+1**: strange sea quark + degenerate up/down quarks as light as possible (standard)
- **n_f=2+1+1**: add charmed sea quark (in production)

n_f=2+1 sea quarks

- Major breakthrough for lattice QCD
- **Realistic QCD calculations** that include the effects of the dynamical u, d, & s quarks in the vacuum



Lattice QCD simulations now regularly include 2+1 sea quarks



[HPQCD, MILC, & Fermilab Lattice Collaborations Phys.Rev.Lett.92:022001,2004]

"GOLD-PLATED" lattice processes

- Easiest quantities to compute **with controlled systematic errors and high precision** have only hadron in initial state and at most one hadron in final state, where the hadrons are stable under QCD (or narrow and far from threshold)
  - Includes meson masses, decay constants, semileptonic and rare decay form factors, and neutral meson mixing parameters
  - Enable determinations of all CKM matrix elements except $|V_{tb}|$
  - Excludes ρ, K^* mesons and other resonances, fully hadronic decays such as $K\to\pi\pi$ and $B\to DK$, and long-distance dominated quantities such as D^0-mixing
- **Although many nucleon matrix elements are gold plated, calculations are generally more challenging than for mesons**
  - Computationally demanding because statistical noise in correlation functions grows rapidly with Euclidean time
  - Extrapolation to physical light-quark masses difficult because baryon chiral perturbation theory converges less rapidly

Systematics in lattice calculations

(1) Monte carlo statistics & fitting

(2) Tuning lattice spacing and quark masses

- Require that lattice results for a few quantities (*e.g.* m_π, m_K, m_{Ds}, m_{Bs}, f_π) agree with experiment

(3) Matching lattice gauge theory to continuum QCD

- Use fixed-order lattice perturbation theory, step-scaling, or other partly- or fully-nonperturbative methods

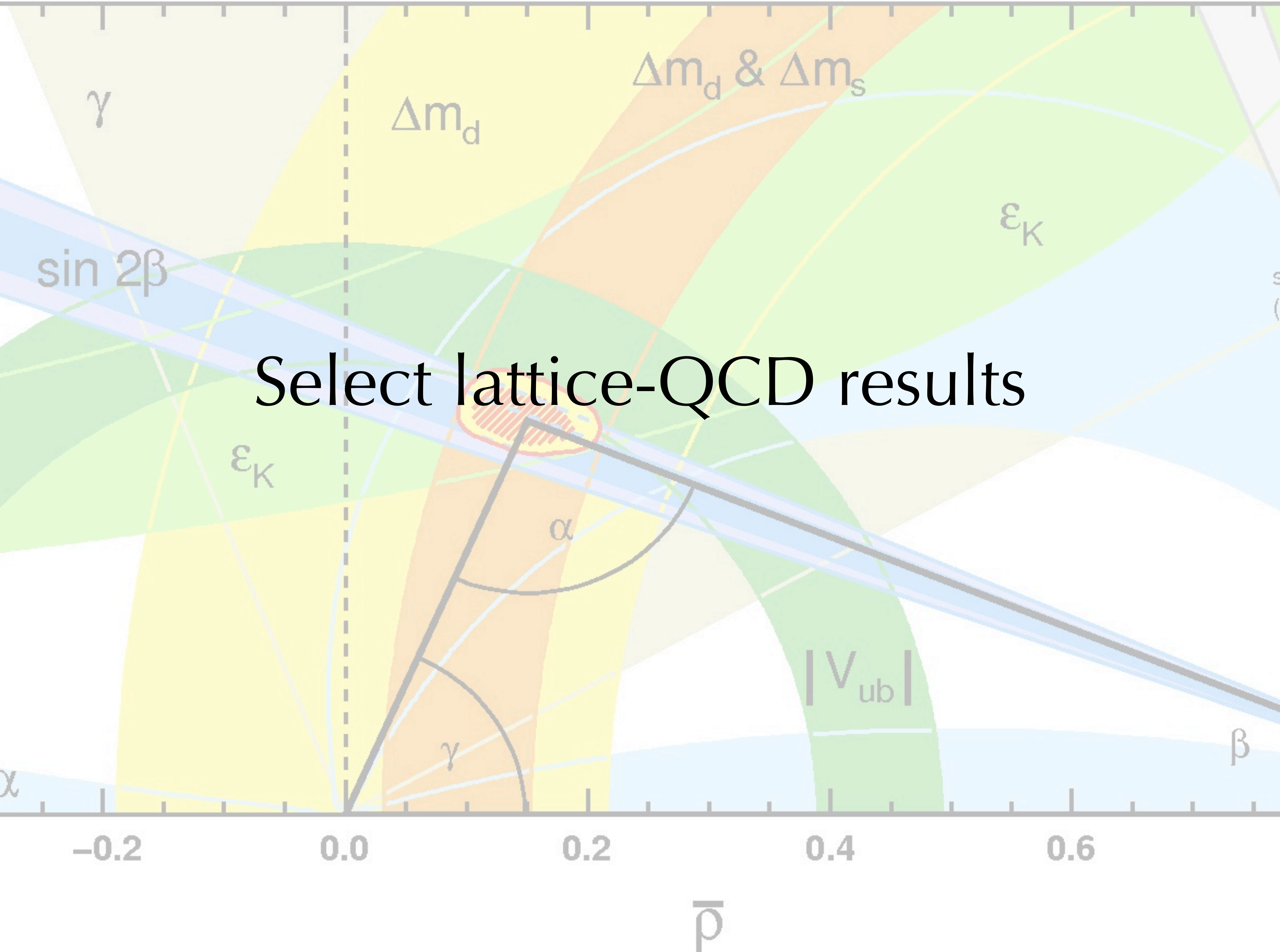
(4) Chiral extrapolation to physical up, down quark masses

(5) Continuum extrapolation

- Simulate at a sequence of quark masses & lattice spacings and extrapolate to $m_{lat} \to m_{phys}$ & $a \to 0$ using functional forms derived in chiral perturbation theory

- Verify understanding and control of systematic uncertainties in lattice calculations by comparing results for known quantities with experiment

Select lattice-QCD results



Scope of lattice QCD

- Nonperturbative QCD dynamics are quantitatively important to many areas of particle and nuclear physics

Flavor physics

- Neutral meson decays and mixing
- Leptonic decay constants & semileptonic form factors
- CKM matrix elements

Nucleon matrix elements

- Neutron EDM
- Proton & neutron decay
- Nucleon axial charge

Heavy-ion physics

- QCD phase diagram
- Equation of state

Muon physics

- Hadronic vacuum polarization contribution to g-2
- Hadronic light-by-light contribution to g-2

Hadronic physics

- Meson and baryon spectrum
- Hadron-hadron scattering lengths and phase shifts

Standard-Model parameters

- Quark masses
- Strong coupling constant

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Nucleon matrix elements

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Here describe some of the most mature and quantitatively impressive calculations

Heavy-ion physics

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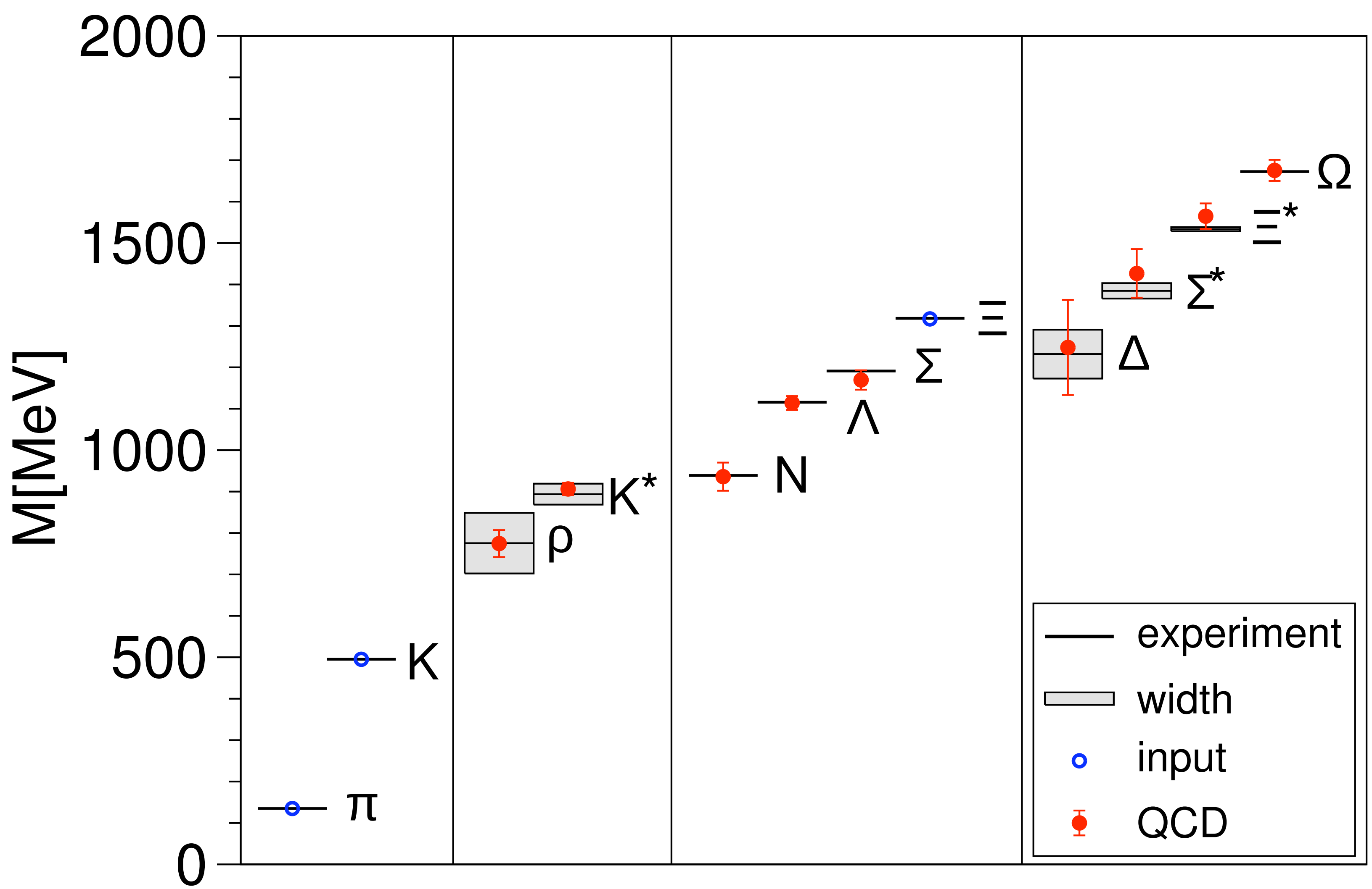
Light-hadron spectrum

[BMW Collaboration, Science 322 (2008) 1224-1227]

- Light hadrons constitute more than 99% of the mass of the visible universe



- Masses much larger than constituent quark masses, so primarily due to energy stored in gluon field and to quarks' kinetic energy

- **Agreement within 1% of experiment nontrivial test of nonperturbative QCD dynamics**

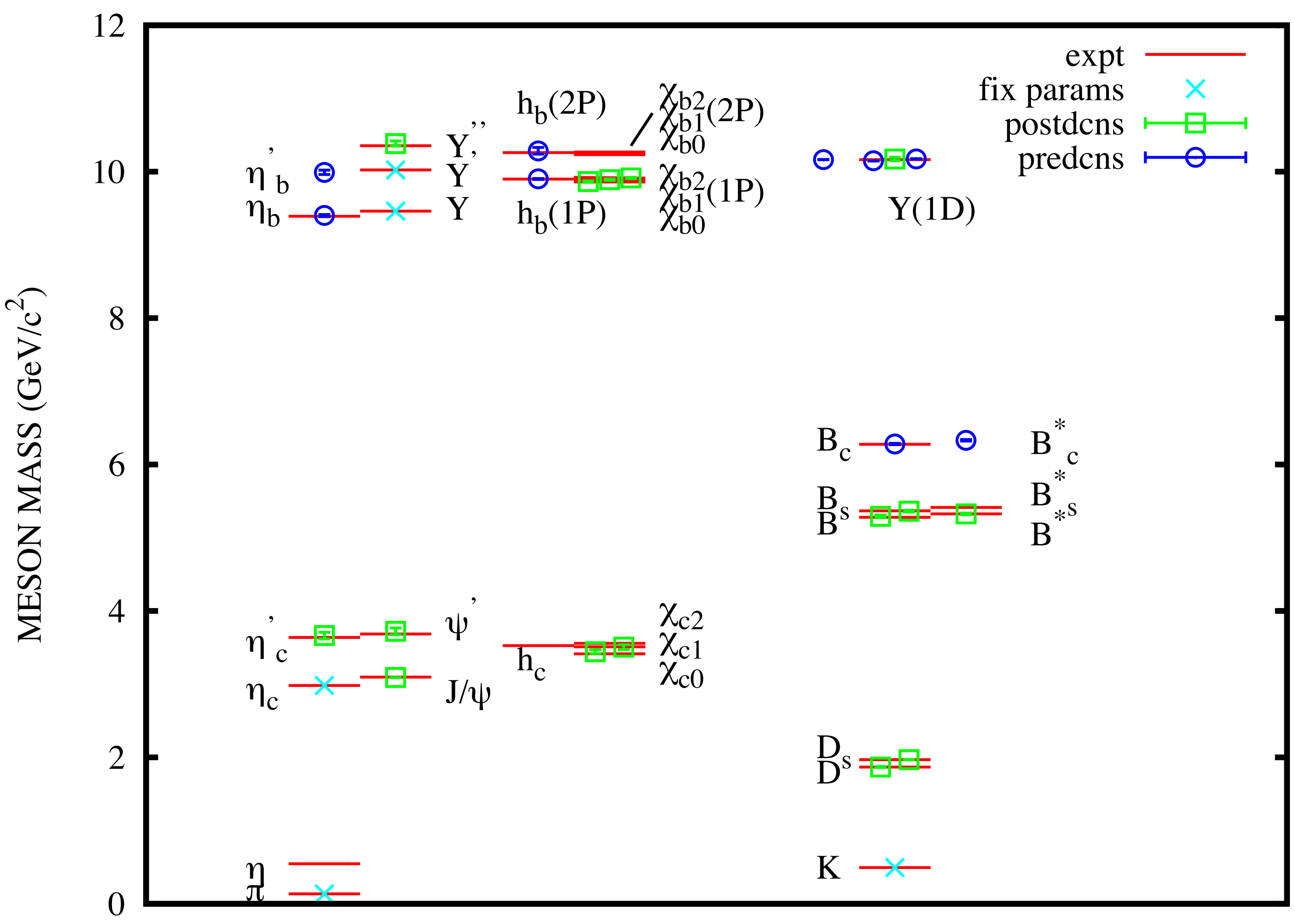
Heavy-hadron spectrum

[HPQCD Collaboration, arXiv:1203.3862 (C.Davies Lattice 2011 review)]

- Lattice-QCD calculations of heavy quarks complicated because the b- & c-quark masses are larger than the typical inverse lattice spacing in current simulations

- Simplest lattice actions will have large discretization errors $\propto (am_Q)^n$, so use knowledge of heavy-quark and/or nonrelativistic limits of QCD to control discretization errors

- **Spectrum provides essential test of methods for lattice heavy-quark frameworks**



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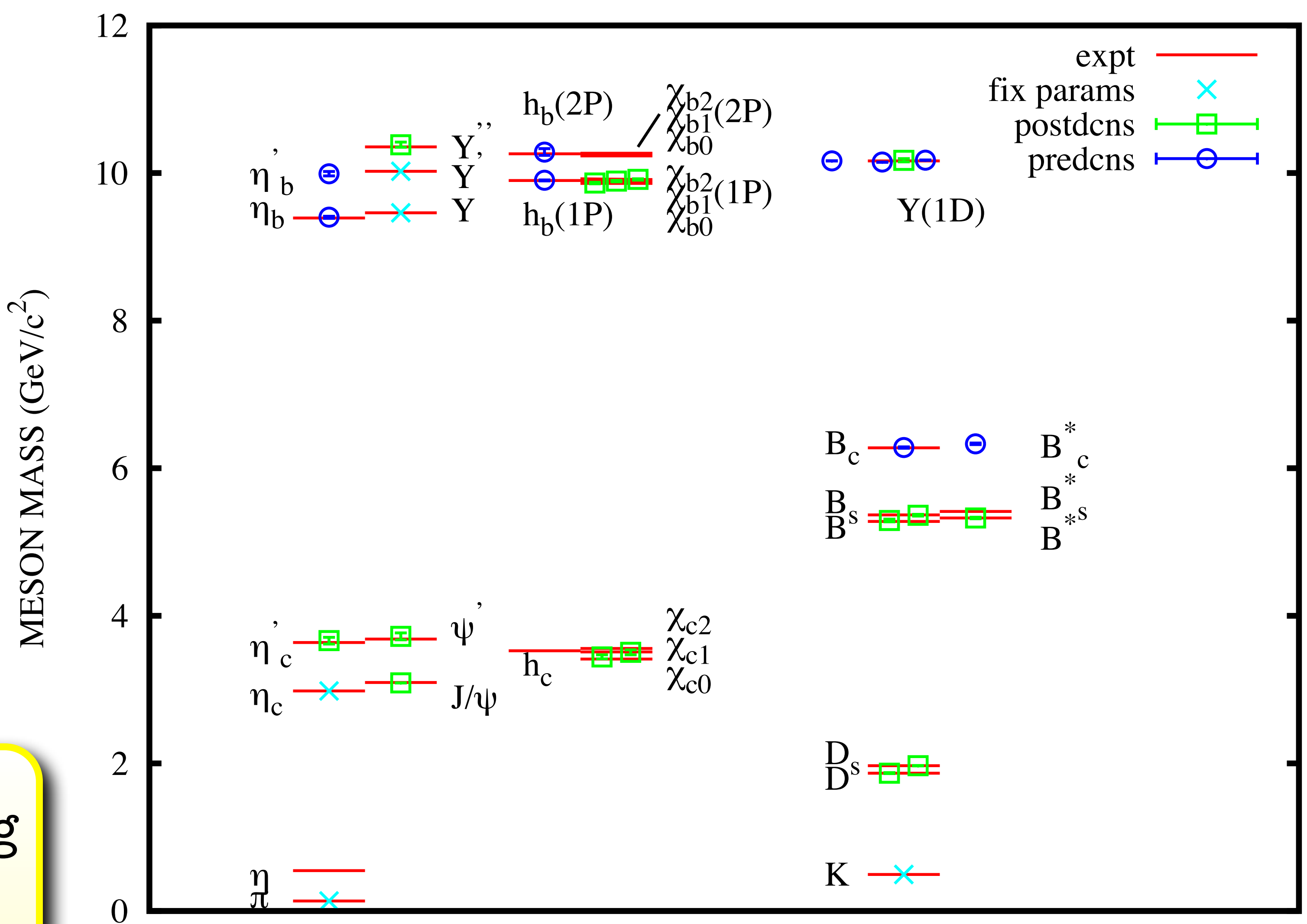
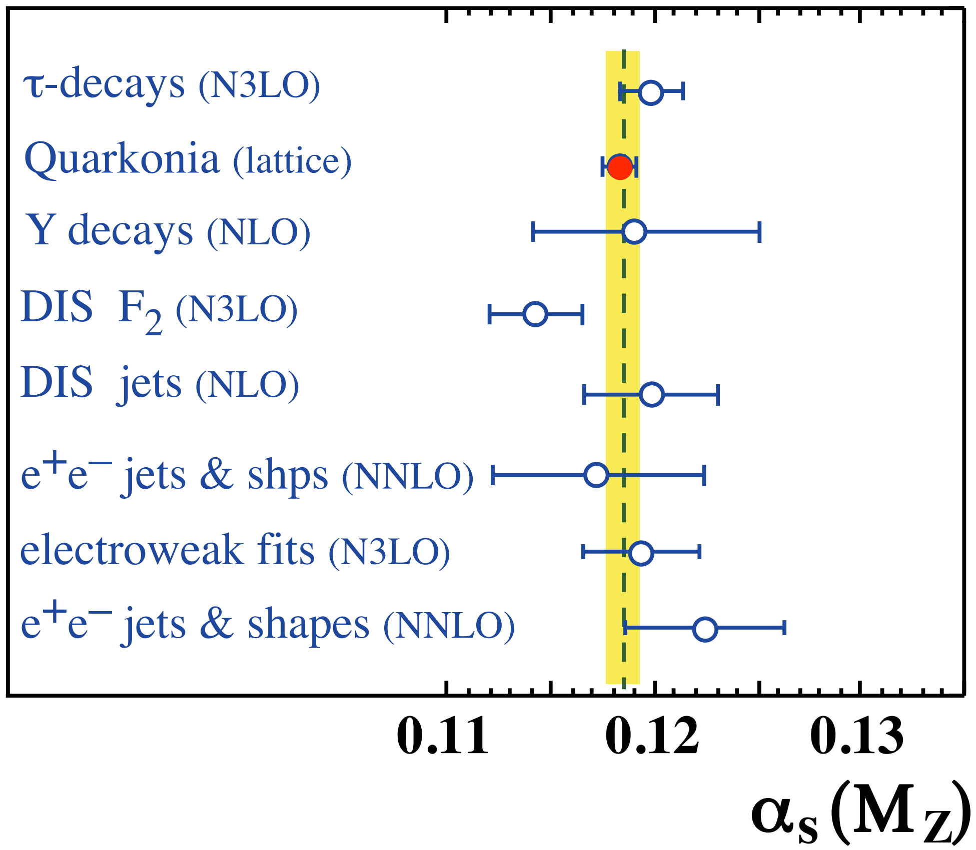


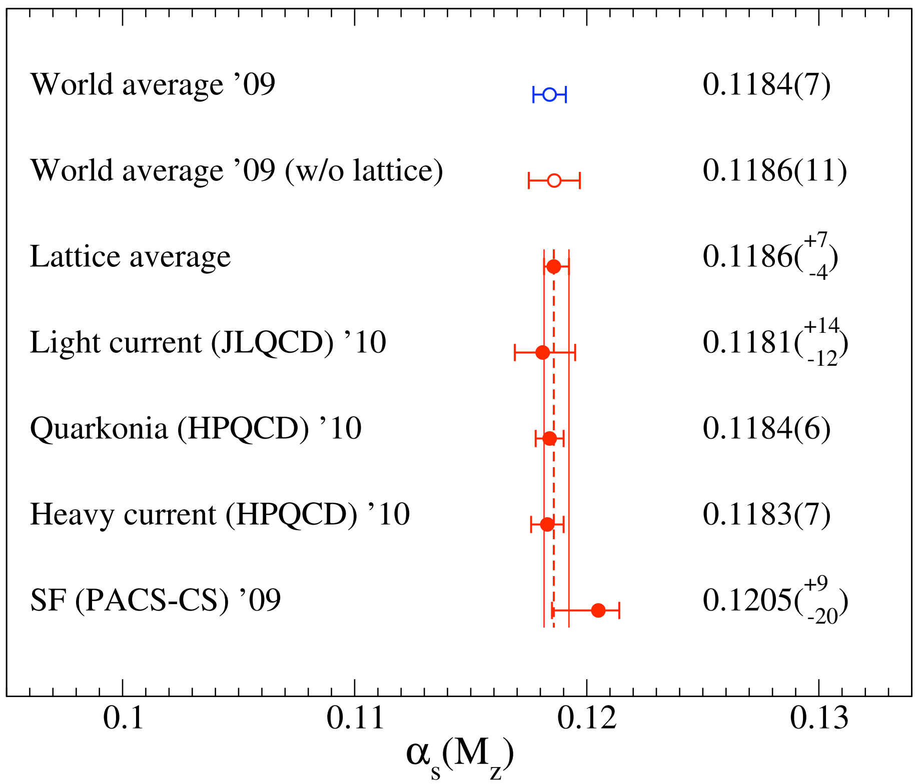
NB: lattice spacings now becoming sufficiently fine that can simulate charm quarks with highly improved light-quark actions

The strong coupling constant

[Bethke Eur.Phys.J. C64 (2009)]



[Shintani, PoS(Lattice 2011)001]

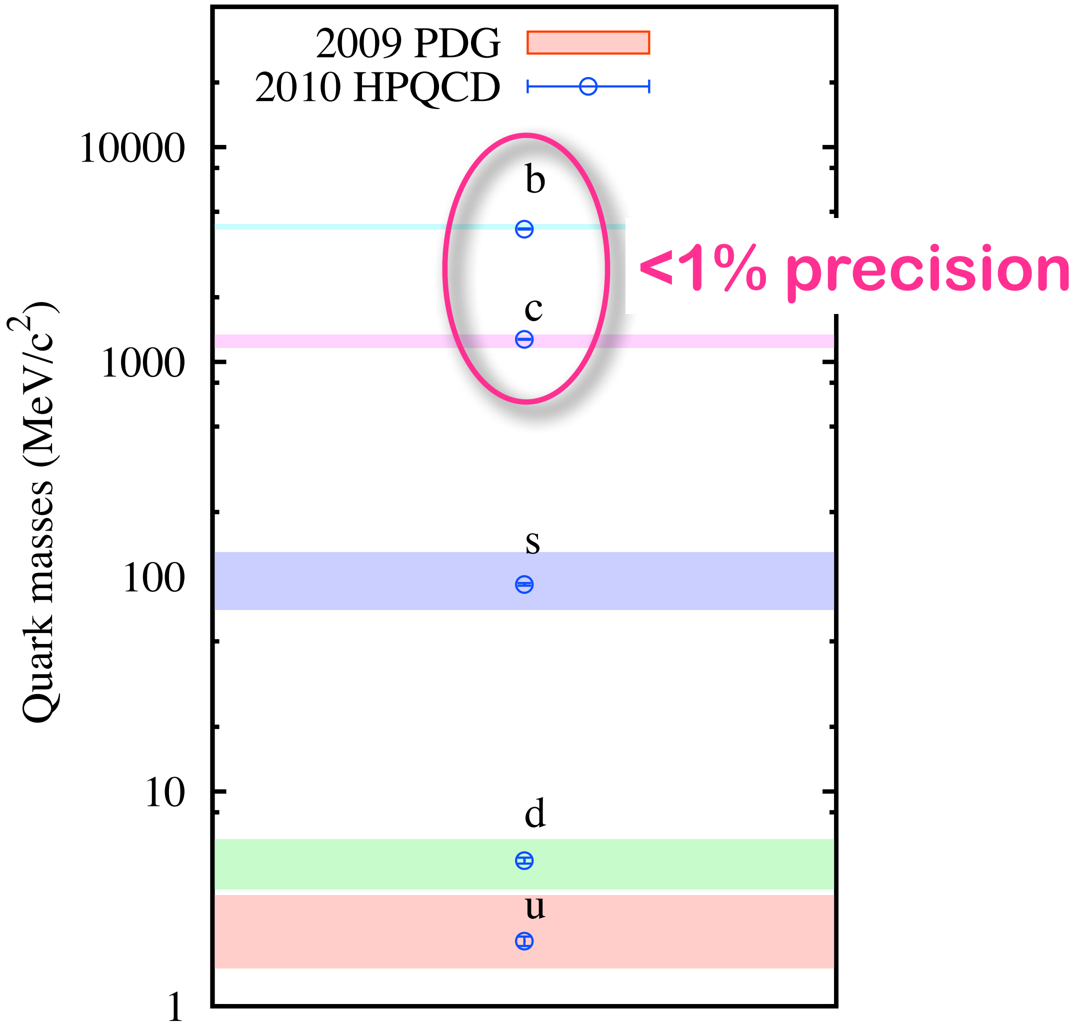


- Lattice calculation of $\alpha_S(M_Z)$ (**RED**) agrees with experimental determinations, and has smaller uncertainties
- Several independent lattice approaches consistent and with similar precision
- Nontrivial test that **QCD of partons = QCD of hadrons**

Quark masses

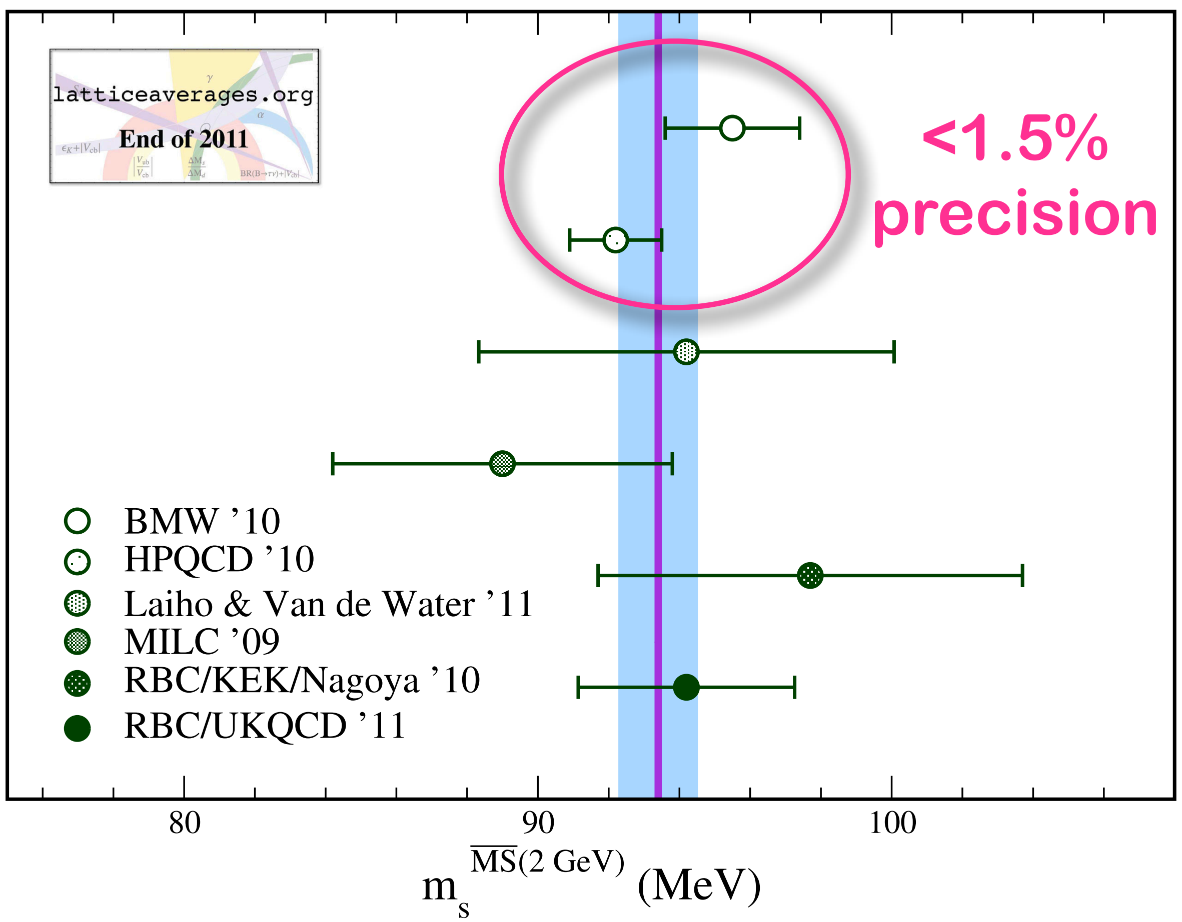
✦ Fundamental parameters that enter Standard-Model and BSM predictions

[HPQCD, PRD 82 (2010) 034512]



b- & c-quark masses agree with non- lattice determinations from $e^+e^- \to$ hadrons

[Laiho, Lunghi, RV, arXiv:1204.0791]



Light-quark masses verified by several independent lattice calculations

Prediction: the B_c meson mass

Lattice-QCD "prediction" =

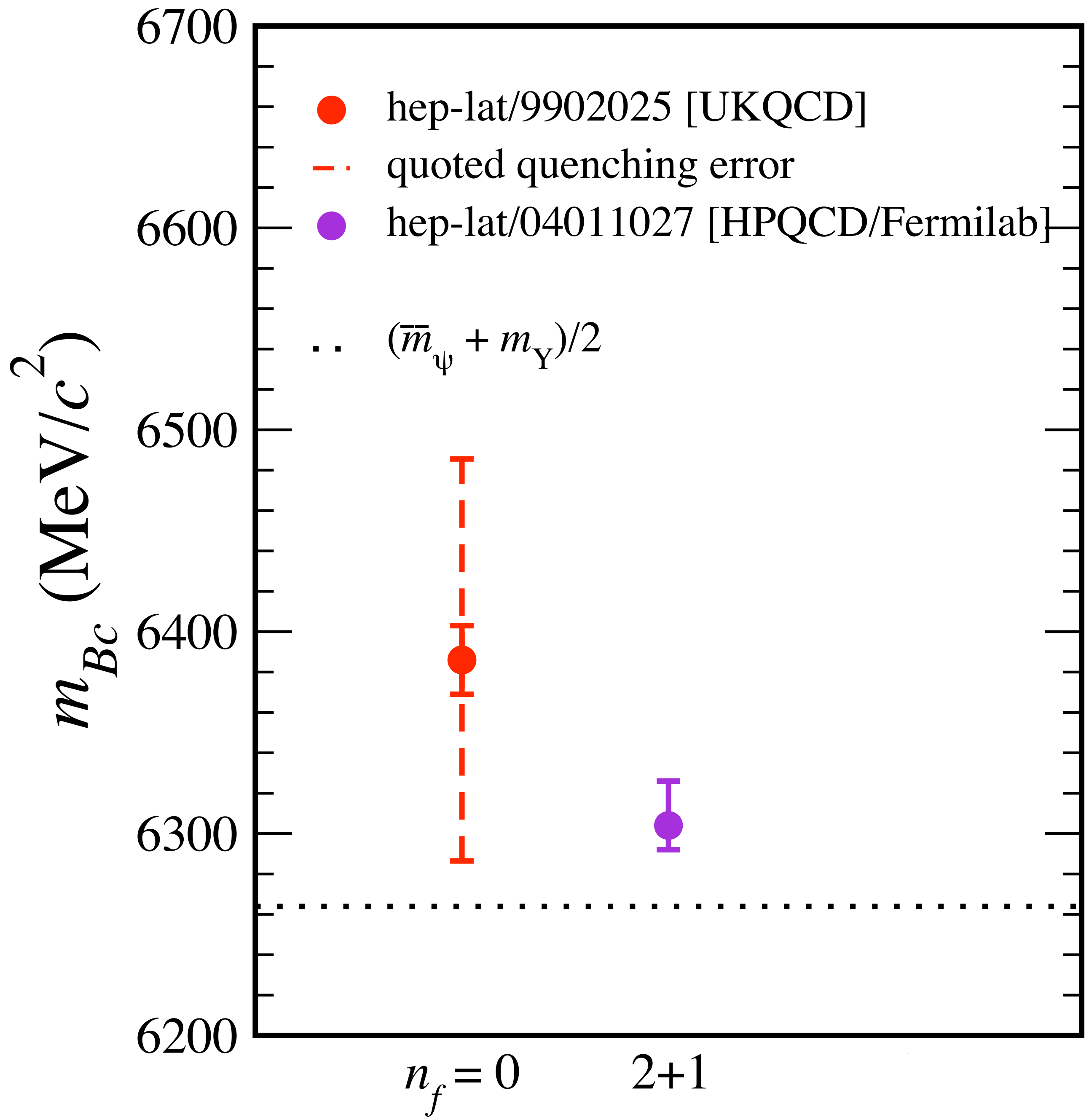
any lattice result that was obtained before the corresponding experimental measurement was comparably precise

Prediction: the B_c meson mass

[HPQCD & Fermilab Lattice Collaborations, Phys.Rev.Lett. 94 (2005) 172001]

November 2004:

Lattice QCD calculation

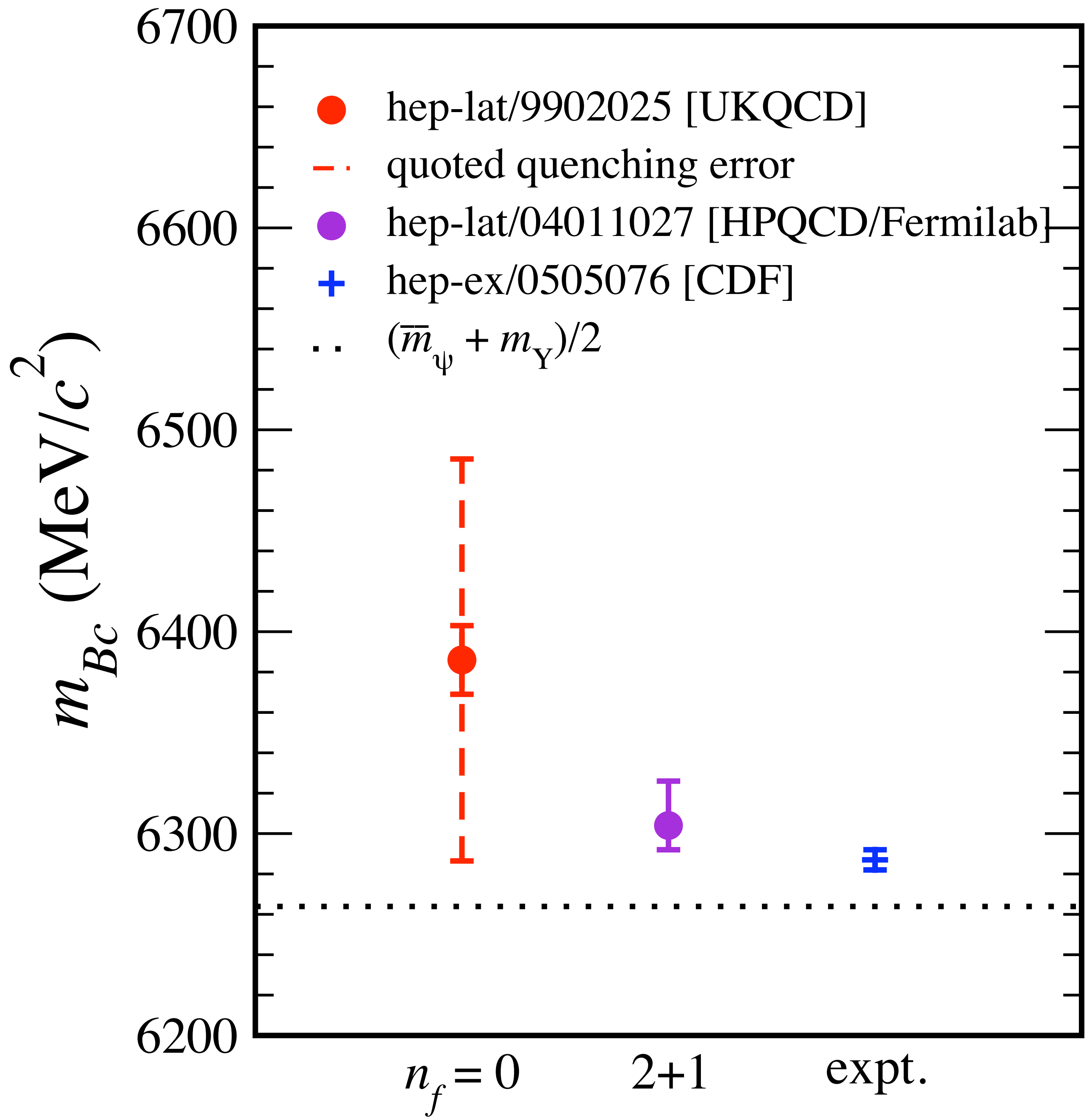


Prediction: the B_c meson mass

[HPQCD & Fermilab Lattice Collaborations, Phys.Rev.Lett. 94 (2005) 172001]

December 2004:

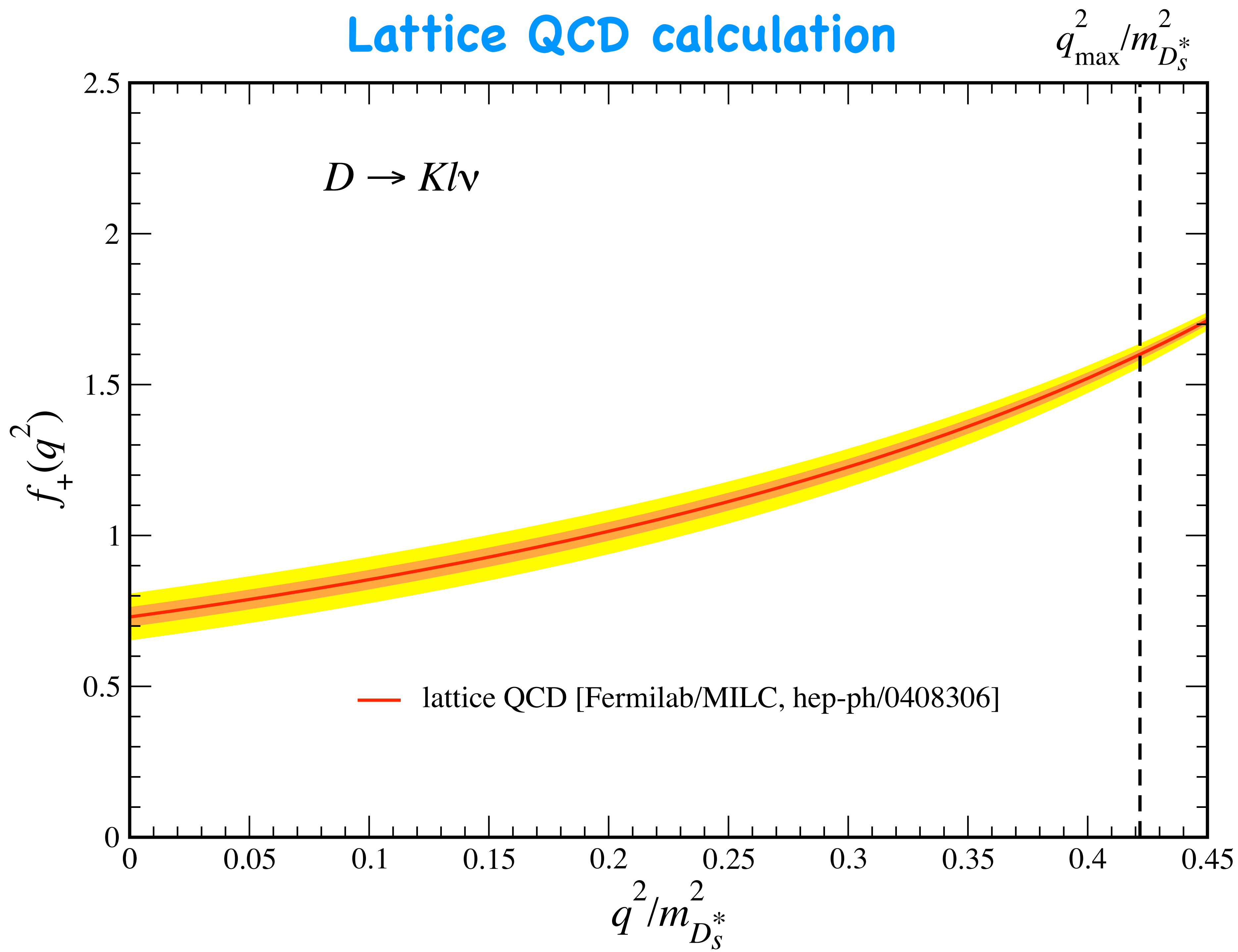
CDF measurement



Prediction: the D→Kℓν form factor

[Fermilab Lattice, MILC, & HPQCD Collaborations, Phys.Rev.Lett. 94 (2005) 011601]

August 2004:
Lattice QCD calculation

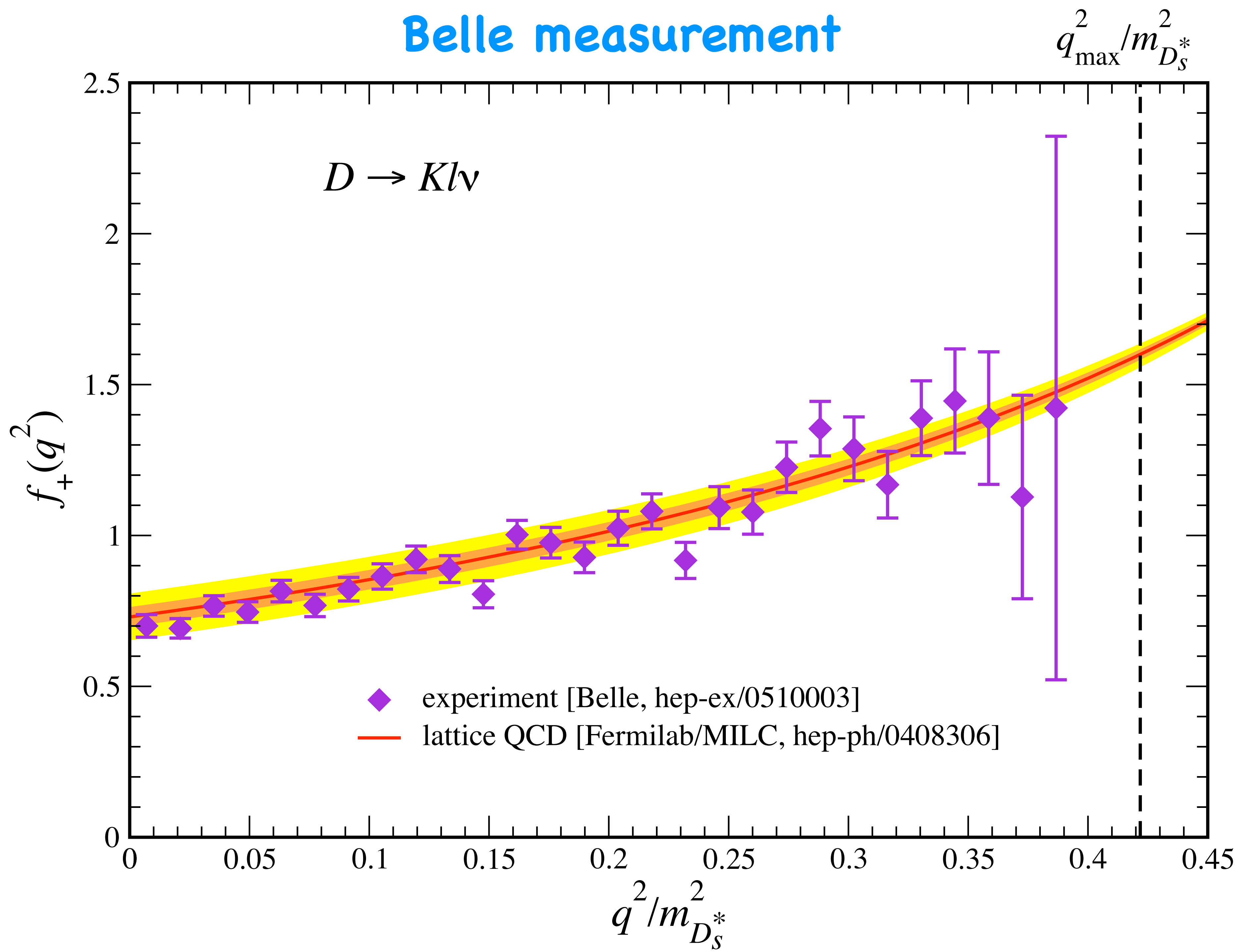


Prediction: the $D \to K\ell\nu$ form factor

[Fermilab Lattice, MILC, & HPQCD Collaborations, Phys.Rev.Lett. 94 (2005) 011601]

October 2005:

Belle measurement

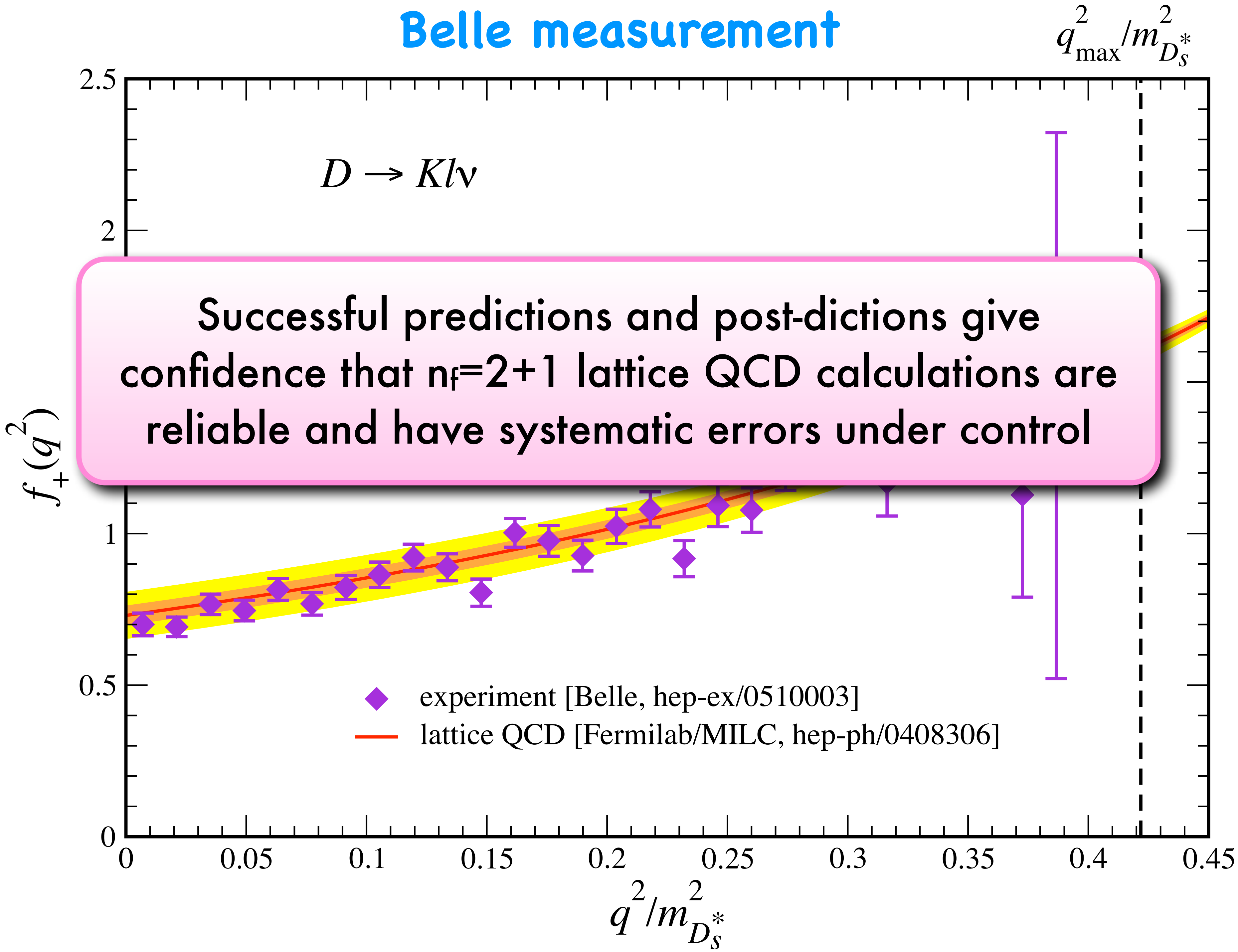


Prediction: the D→Kℓν form factor

[Fermilab Lattice, MILC, & HPQCD Collaborations, Phys.Rev.Lett. 94 (2005) 011601]

October 2005:

Belle measurement



Successful predictions and post-dictions give confidence that n_f=2+1 lattice QCD calculations are reliable and have systematic errors under control

Flavor physics

- "Gold-plated" lattice processes enable determinations of all Cabibbo-Kobayashi-Maskawa matrix elements except $|V_{tb}|$

  *Neutral kaon mixing also gold-plated and can be used to obtain the CKM phase (ρ, η)

$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to \ell\nu & K \to \ell\nu & B \to \ell\nu \\ & K \to \pi\ell\nu & B \to \pi\ell\nu \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d|\bar{B}_d\rangle & \langle B_s|\bar{B}_s\rangle & \end{pmatrix}$$

(Experiment) = (known) x (CKM factors) × (Hadronic Matrix Element)

$$\Delta m_{(d,s)}\,,\quad \frac{d\Gamma(D\to K\ell\nu)}{dq^2},\ \frac{d\Gamma(B\to\pi\ell\nu)}{dq^2},\quad \frac{d\Gamma(B\to D^{(*)}\ell\nu)}{dw},\ldots$$

Absorb nonperturbative QCD effects into quantities such as decay constants, form factors, and bag-parameters that must be computed with **LATTICE QCD**

First-row CKM unitarity

- n_f=2+1 lattice calculations of the leptonic decay constant ratio f_K/f_π and the semileptonic form factor $f_+^{K\pi}(0)$ **allow the world's best determinations of $|V_{ud}|/|V_{us}|$ & $|V_{us}|$**
  [BMW, PRD 81, 054507 (2010);
  HPQCD, PRL 100, 062002 (2008);
  MILC, arXiv:1012.0868;
  ETMC, PRD 80 (2009) 111502;
  RBC/UKQCD, EPJC 69 (2010) 159-167]

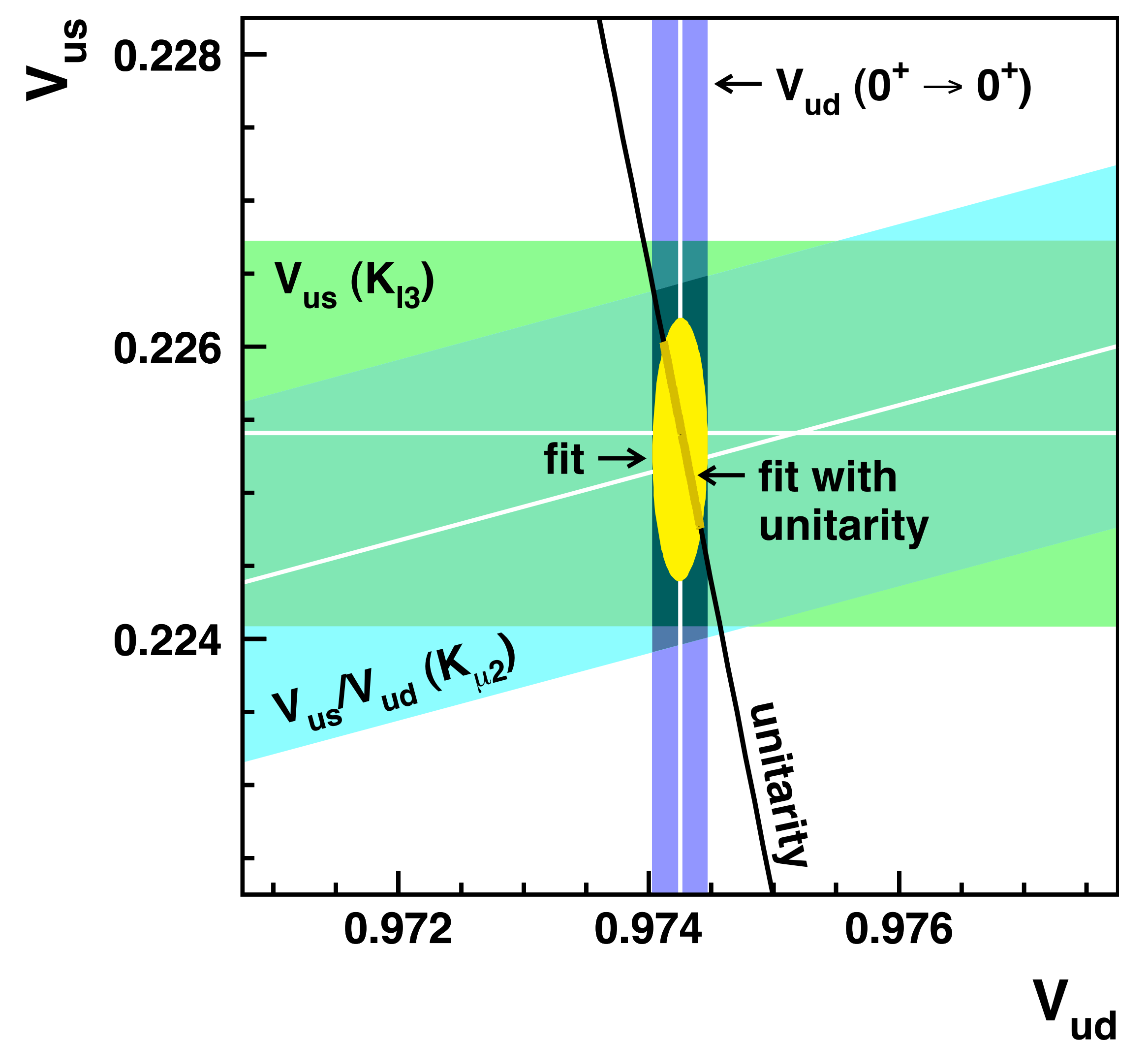
- Can use these results to test the unitarity of the first row of the CKM matrix
  - $|V_{ub}| \sim \mathcal{O}(10^{-3})$, so essentially constraint on relationship between $|V_{ud}|$ & $|V_{us}|$

- Current lattice-QCD & experimental results consistent with unitarity at the sub-percent level:

$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0001(6)}$$

[Flavianet, Eur.Phys.J. C69 (2010)]

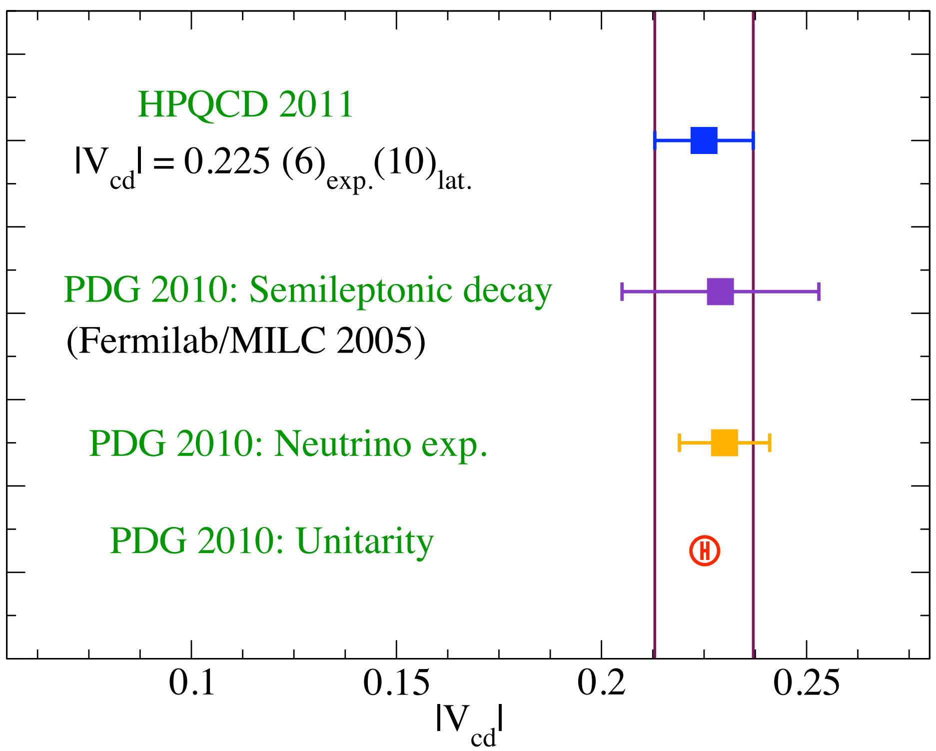
χ^2/d.o.f. = 0.012, p = 99%

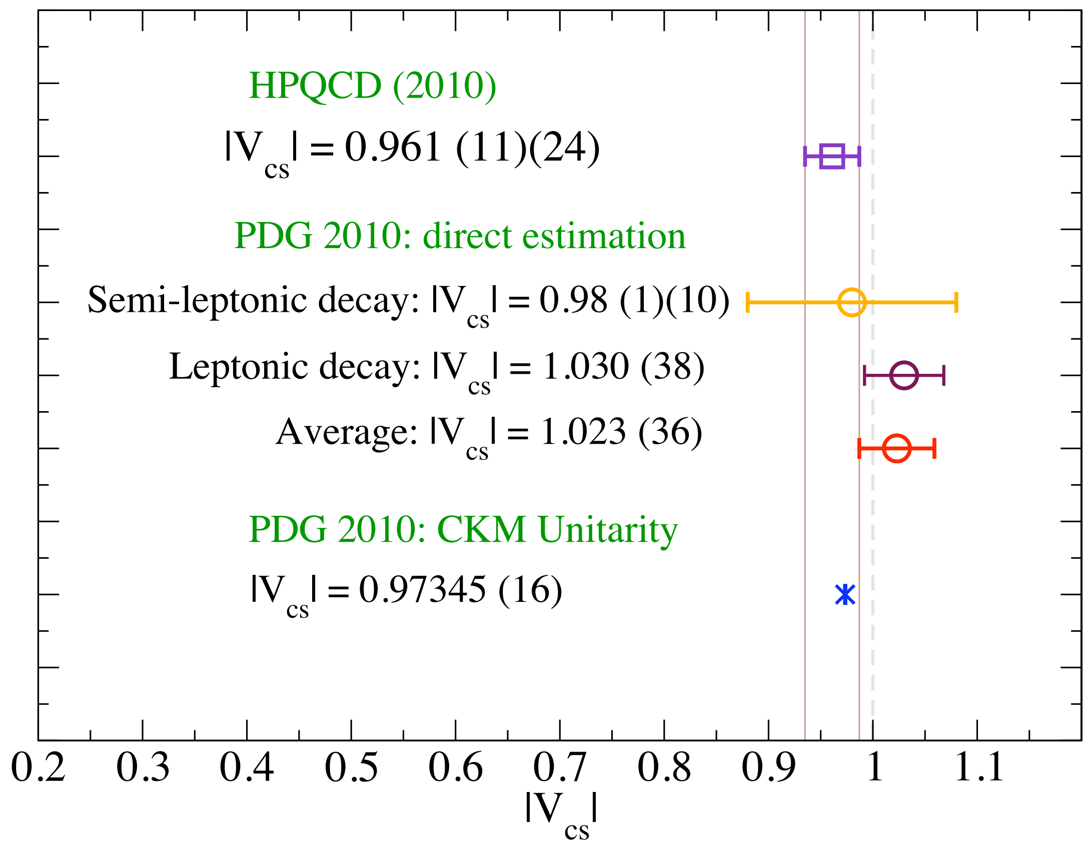


Second-row CKM unitarity

[Na *et al.*, PRD 82 (2010) 114506; PRD 84 (2011) 114505]

- Lattice-QCD calculations of $D \to \pi \ell \nu$ and $D \to K \ell \nu$ form factors factors can be combined with experimentally-measured branching fractions to obtain $|V_{cd}|$ and $|V_{cs}|$
- HPQCD Collaboration recently developed a new method for obtaining the form factor at zero momentum transfer (q^2=0) with significantly reduced systematic uncertainties



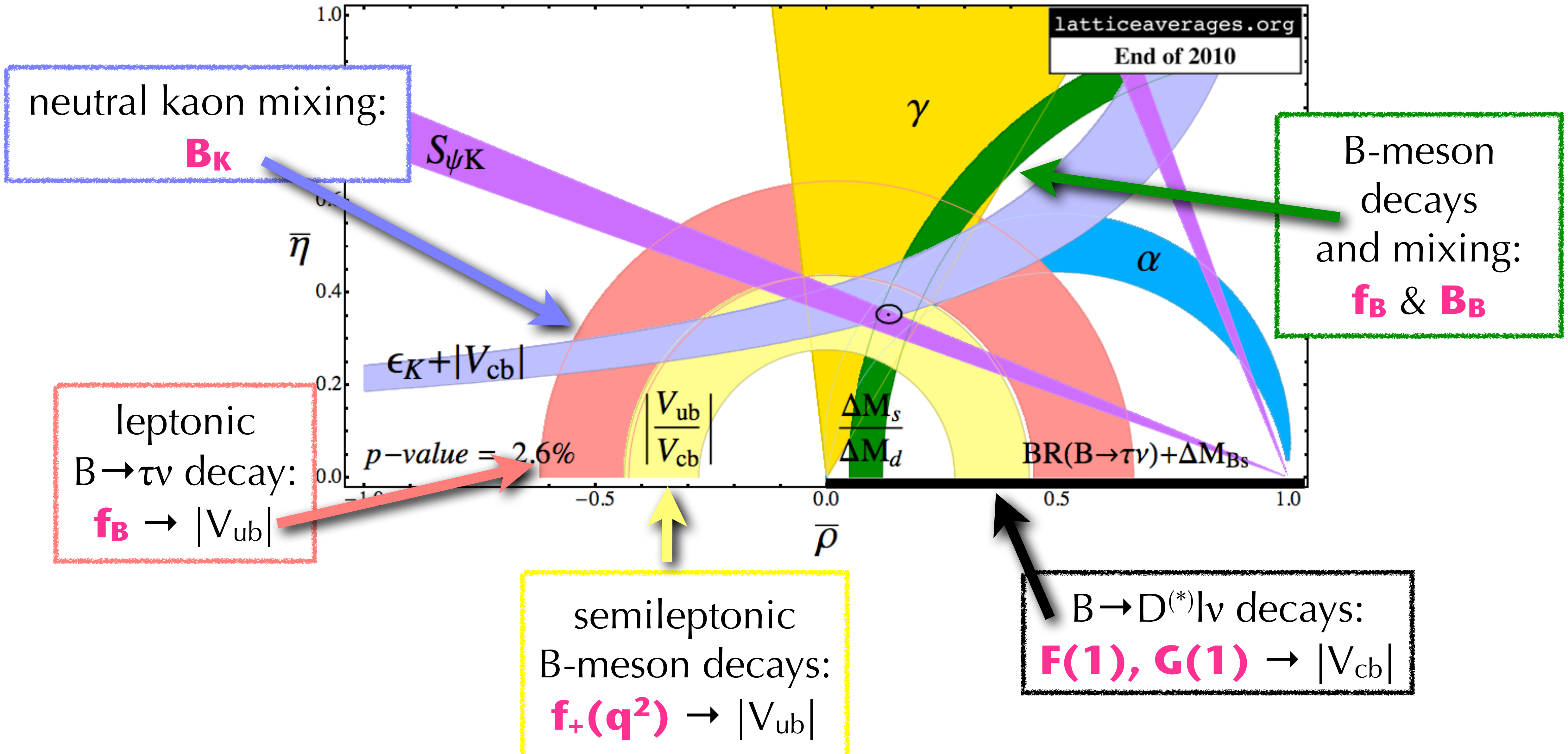


- **Enable a ~5% test of unitarity of 2nd row of the CKM matrix:**

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.976(50)$$

The CKM unitarity triangle

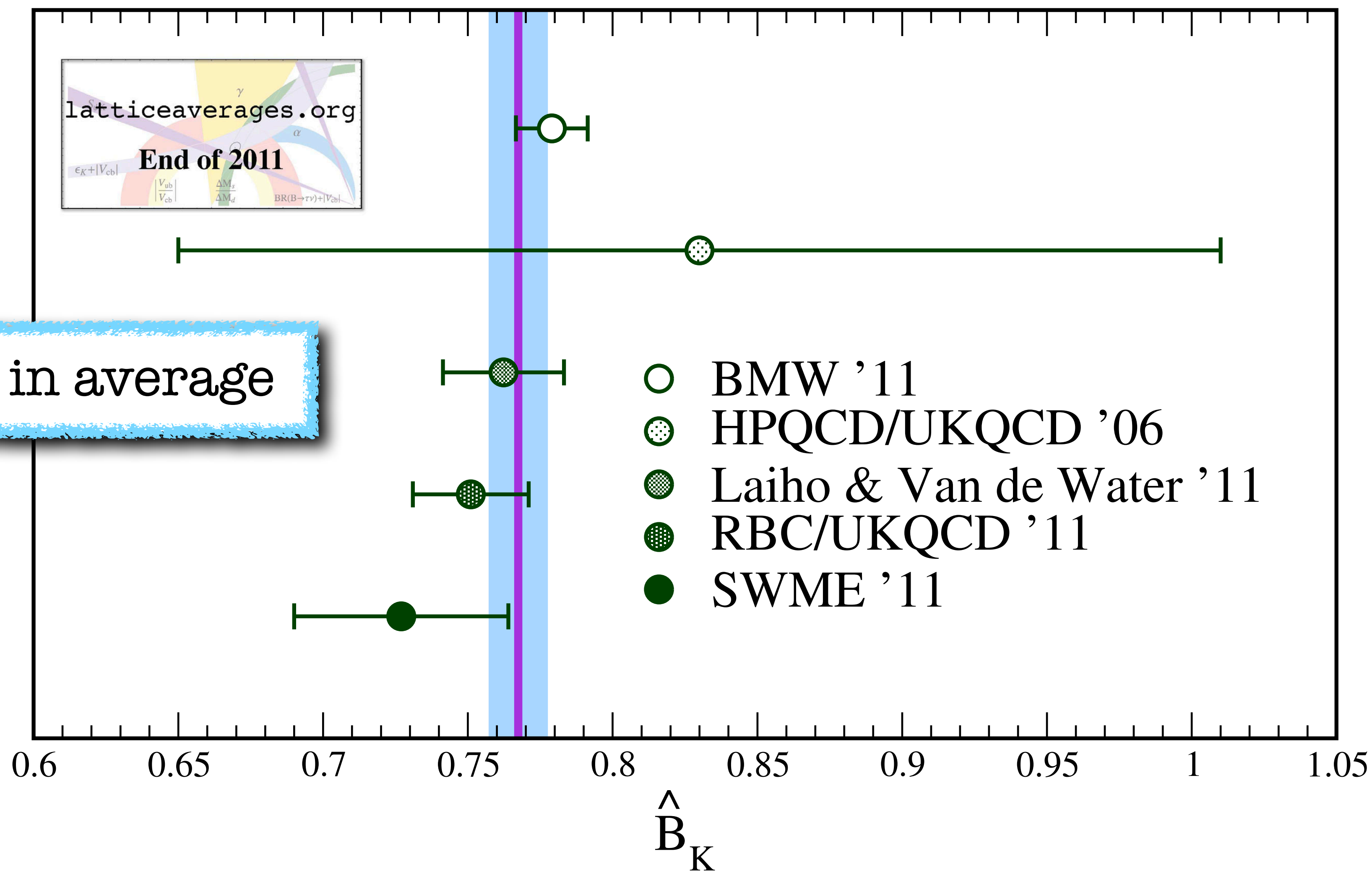
- ✦ Standard approach to search for new physics in the flavor sector is by overconstraining the angles and sides of the CKM unitarity triangle
- ✦ Many constraints require lattice-QCD calculations of **hadronic weak matrix elements**



The kaon mixing parameter B_K

- Until recently, the unitarity-triangle constraint from indirect CP-violation in the neutral kaon system (ϵ_K) was limited by the ~20% uncertainty in lattice QCD calculations of the hadronic matrix element B_K
- Significant theoretical and computational effort has been devoted to improving B_K, and there are **now several independent lattice results that are in good agreement**

~1.3% error in average



Status of the $|\epsilon_K|$ band

- Recent calculation by Brod & Gorbahn [Phys.Rev. D82 (2010) 094026] gives the following error breakdown for $|\epsilon_K|$ in the Standard Model:

$$|\varepsilon_K| = (1.90 \pm 0.04_{\eta_{cc}} \pm 0.02_{\eta_{tt}} \pm 0.07_{\eta_{ct}} \pm 0.11_{\mathrm{LD}} \pm 0.22_{\mathrm{parametric}}) \times 10^{-3}$$

(1) Largest ~10% uncertainty is from parametric error in $A^4 \propto |V_{cb}|^4$

(2) Next-largest error is ~4% uncertainty from η_{ct}, which was just computed to 3-loops (NNLO)

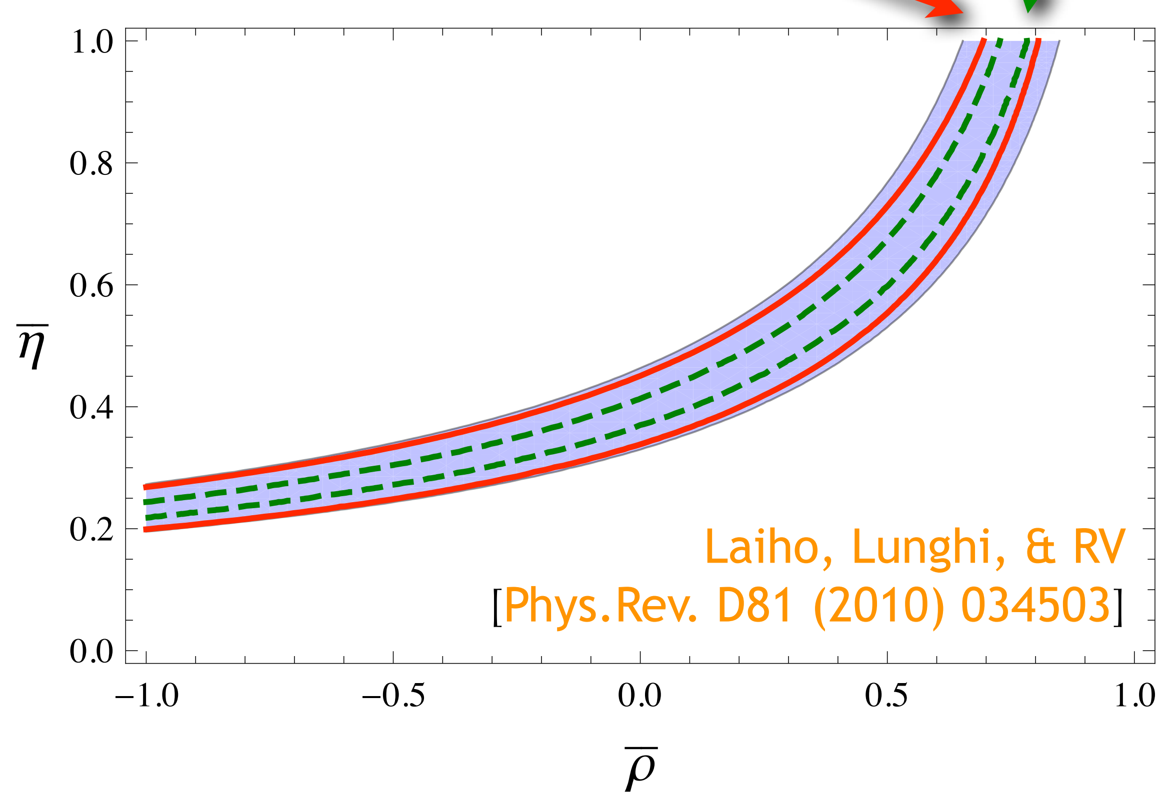
(3) Error from B_K is #3

(4) Other individual error contributions are 2% or less

- Lattice community is moving on to other more challenging kaon physics quantities ...

GREEN: error from B_K only

RED: error from $|V_{cb}|$ only

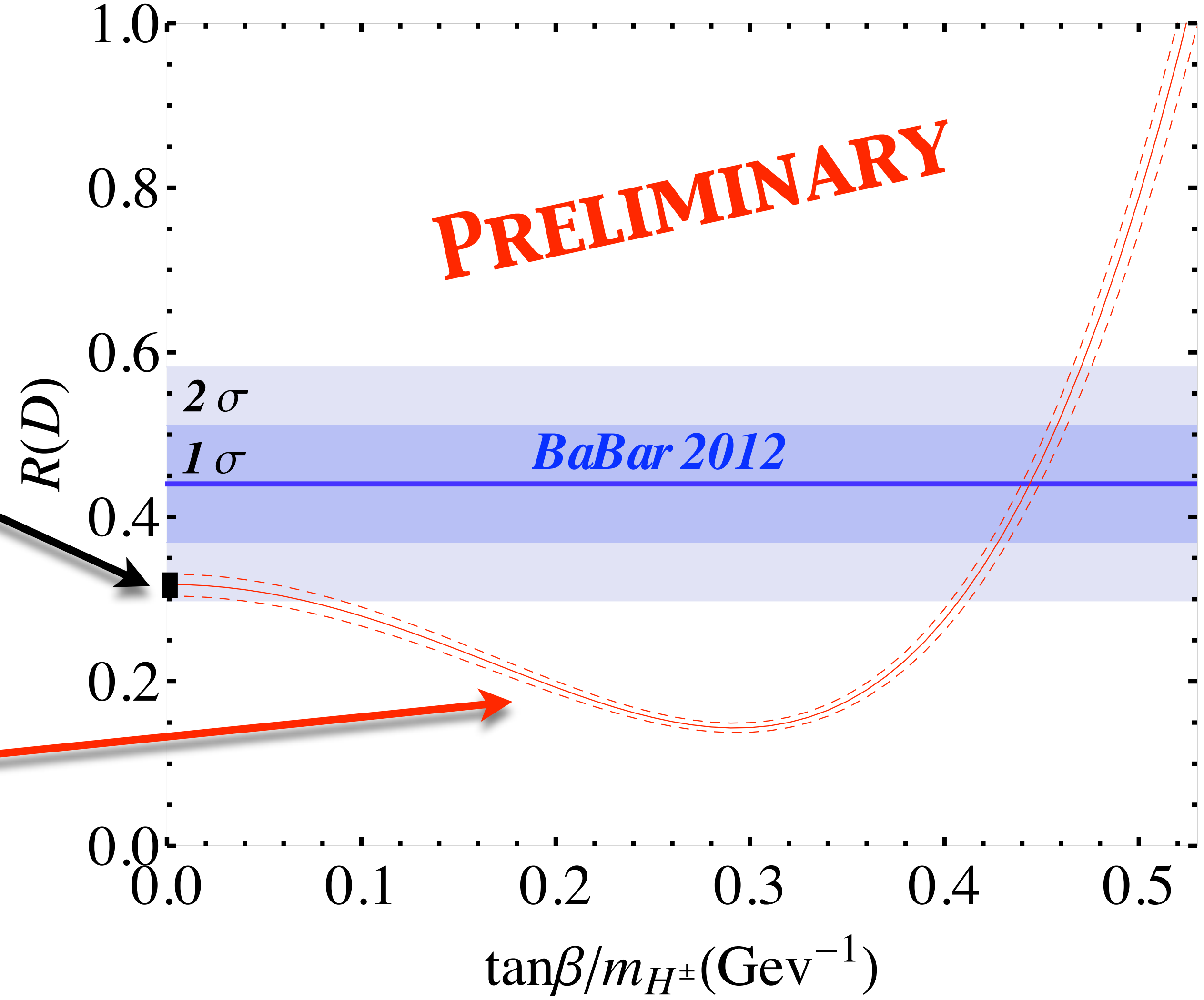


BR(B → Dτν)/BR(B → Dlν)

- Recently BaBar reported on the first observation of B → Dτν and found a 3.4σ discrepancy with the Standard-Model predictions for R(D) = BR(B → Dτν)/BR(B → Dlν) and R(D*) = BR(B → D*τν)/BR(B → D*lν) [arXiv:1205.5442]
- FNAL/MILC Collaboration obtained first SM calculation of R(D) from *ab initio* lattice QCD using form factors $f_+(q^2)$ and $f_0(q^2)$ from arXiv:1202.6346
- Also make predictions for new-physics scenarios such as the two-Higgs-doublet model

[Daping Du for FNAL/MILC]

Standard Model



2HDM prediction from
Tanaka & Watanabe
[arXiv:1005.4306]
+ FNAL/MILC form factors

Lattice QCD for Project X

B_K

Rare kaon decays

- $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ Often called "GOLDEN" MODES because SM branching ratios known to a **precision unmatched by any other quark FCNC processes**

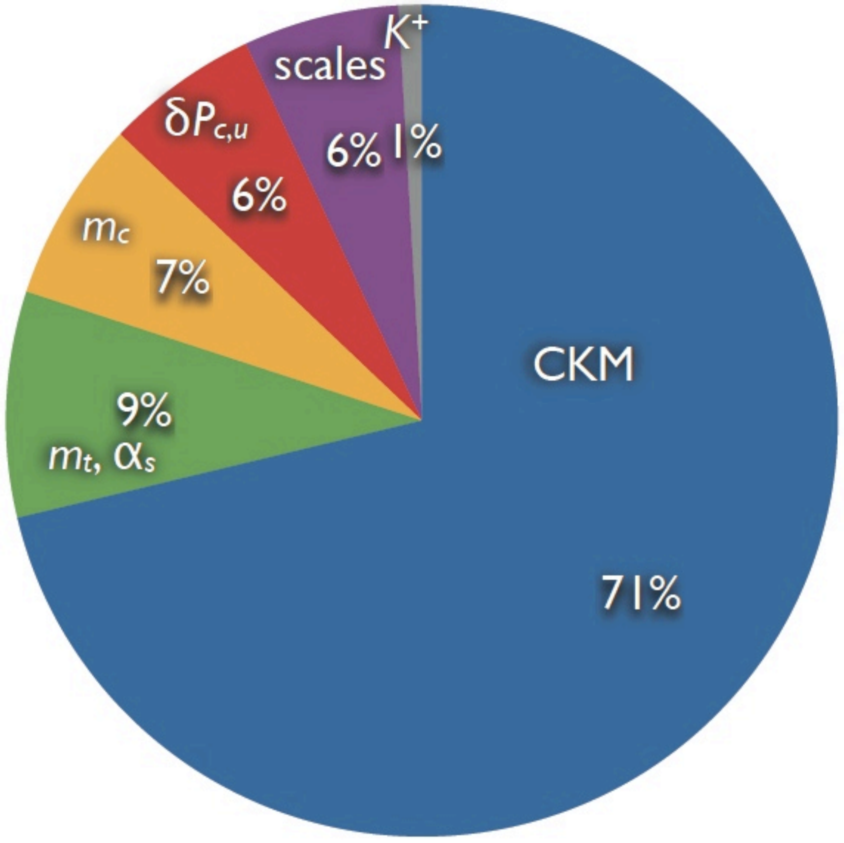
  - Hadronic form factor can be obtained precisely using experimental $K \to \pi\ell\nu$ data combined with chiral perturbation theory [Mescia & Smith, arXiv: 0705.2025]

  ➡ Limited by ~10% parametric uncertainty in $A^4 \propto |V_{cb}|^4$

- By 2014, expect to halve error on $|V_{cb}|$ from lattice-QCD calculations of $B \to D^{(*)}\ell\nu$, reducing error in the SM branching fractions to ~6%

  ➡ Theory error in Standard-Model predictions will be commensurate with expected experimental errors from NA62, KOTO, ORKA, and Project X

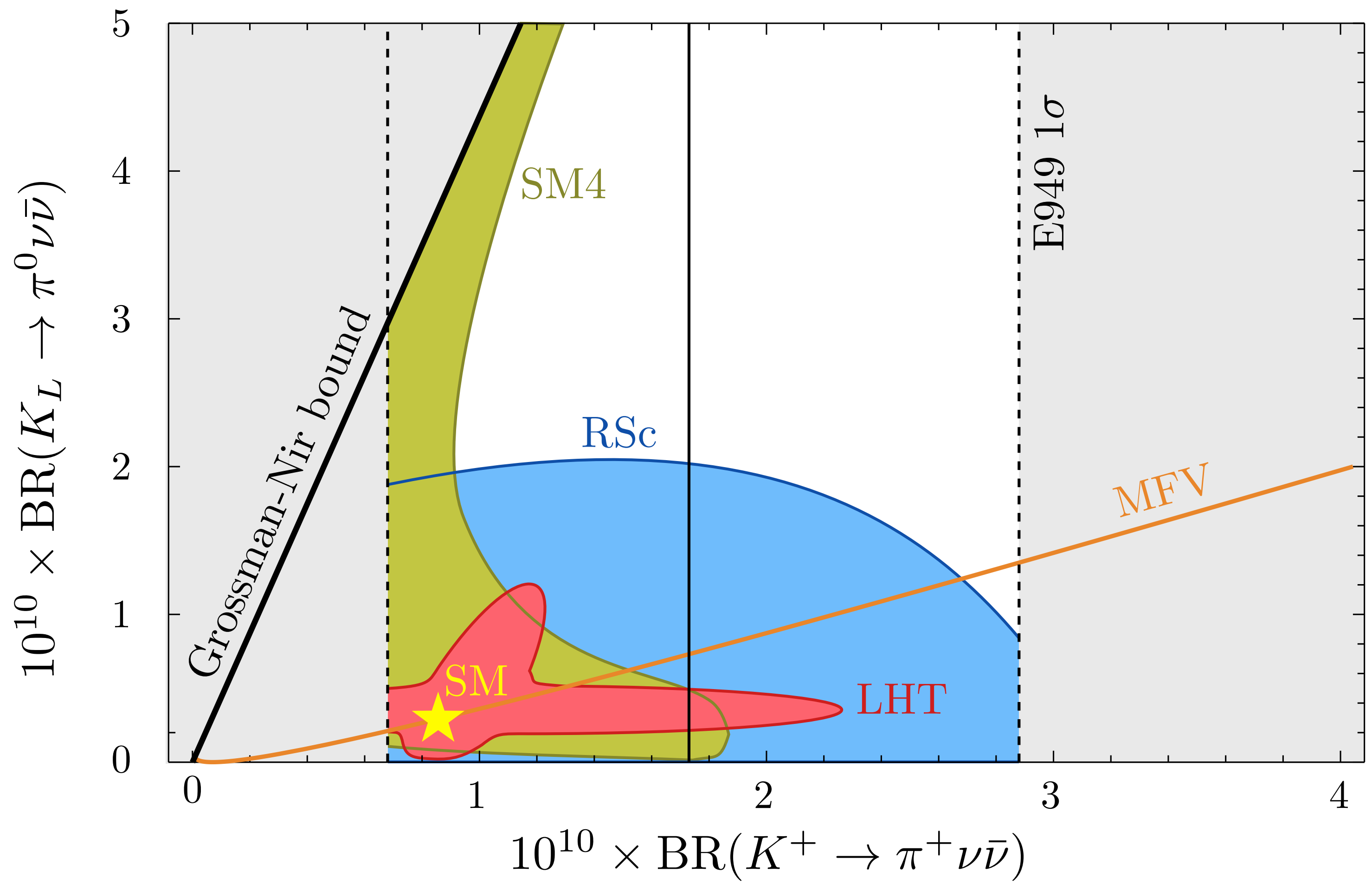
BR($K^+ \to \pi^+ \nu\bar{\nu}$)



[Brod & Gorbahn Phys.Rev. D83 (2011) 034030]

Room for new physics

- Sensitive to Little Higgs models, warped extra dimensions, and 4th generation [Buras, Acta Phys.Polon.B41:2487-2561,2010]



[D. Straub, arXiv:1012.3893 (CKM 2010)]

- **Spectacular deviations from the Standard Model are possible in many new physics scenarios**
- Correlations between the two channels can help distinguish between models

Room for new physics

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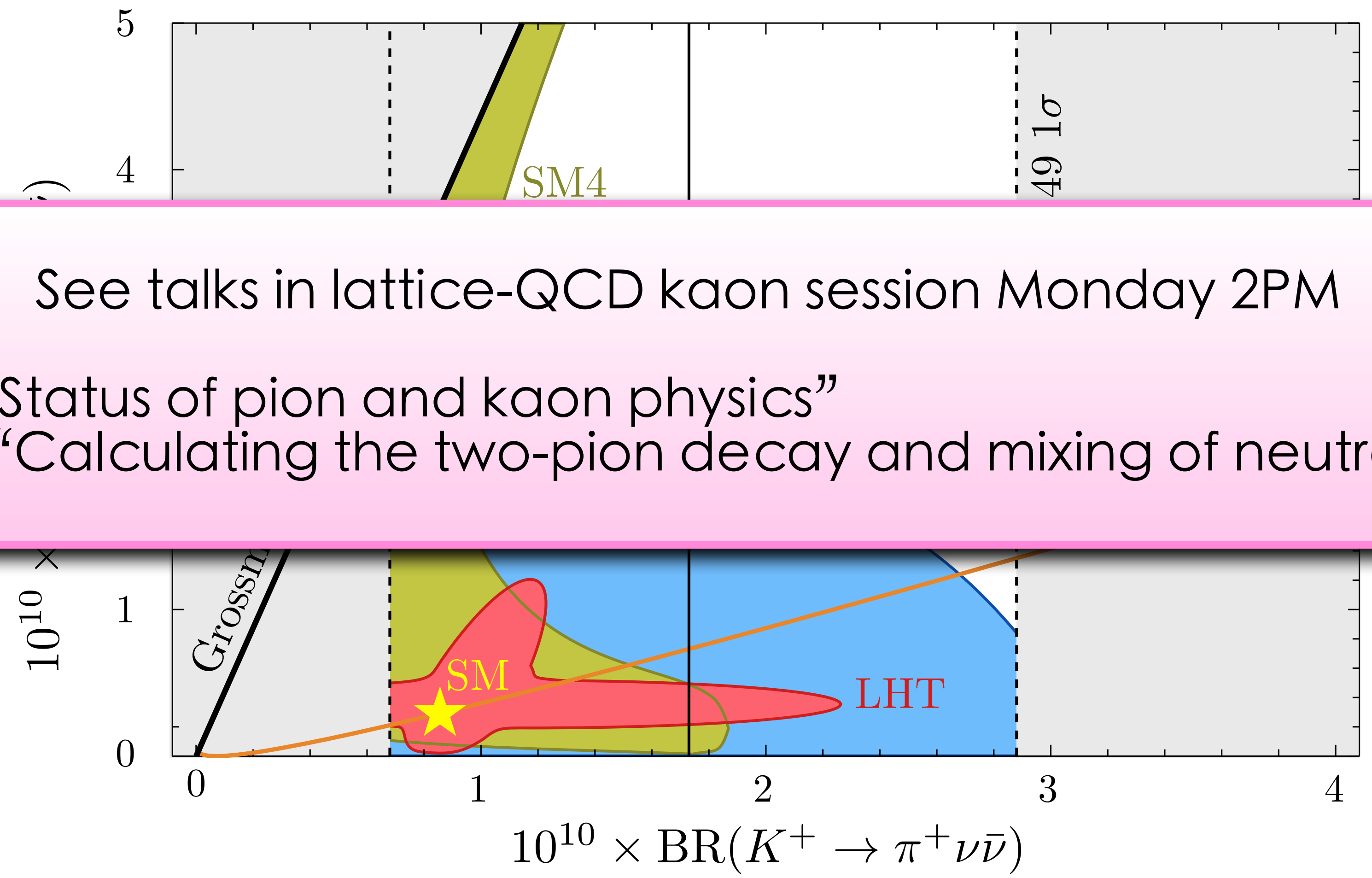


See talks in lattice-QCD kaon session Monday 2PM

- J. Laiho: "Status of pion and kaon physics"
- N. Christ: "Calculating the two-pion decay and mixing of neutral K mesons"

- **Spectacular deviations from the Standard Model are possible in many new physics scenarios**
- Correlations between the two channels can help distinguish between models

Muon g-2

- Currently measured to 0.54 ppm and >3σ discrepancy with Standard Model

$a_\mu^{exp} = 116\ 592\ 089(54)(33) \times 10^{-11}$ [E821]

$a_\mu^{exp} - a_\mu^{SM} = 287(80) \times 10^{-11}$ [3.6σ]

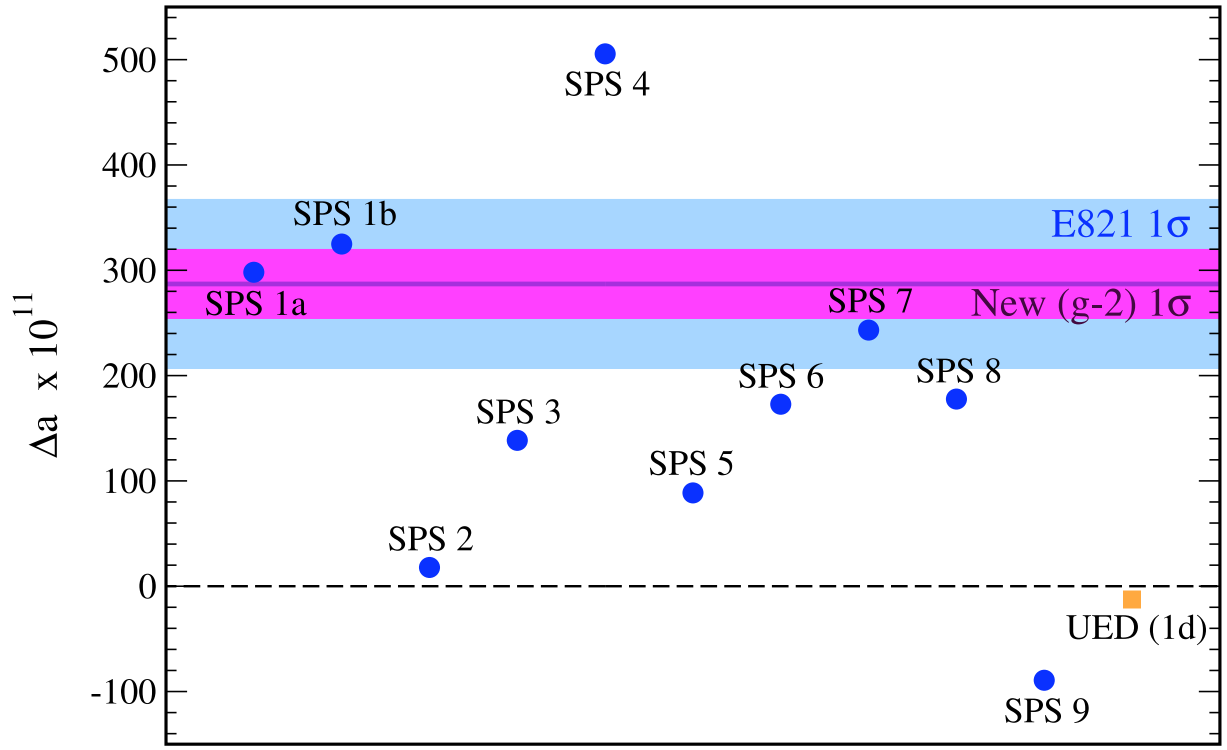
- Extremely **sensitive probe of heavy mass scales in the several hundred GeV range**

- Different new-physics scenarios predict a wide range of contributions to g-2, so precise experimental measurements and theoretical predictions can:

(1) Rule out numerous new-physics scenarios

(2) Distinguish between models with similar LHC signatures

(3) Determine the parameters of the TeV-scale theory that is realized in nature



Lattice-QCD progress on muon g-2

- New g-2 experiment will reduce experimental error to 0.14 ppm
  - A 1% precision or better **lattice calculation of the SM hadronic vacuum polarization contribution can help shed light on the (possible) discrepancy between electron and tau data** and may ultimately replace experimental determinations of a_μ^{HVP}
  - A **10-15% calculation of the SM hadronic light-by-light contribution (and more reliable error estimate!) is crucial** to bring the theoretical errors to below the projected experimental target
- Lattice QCD R&D efforts on both of these contributions are ongoing, *e.g.*:
  - ETM Collaboration [Feng, Jansen, Petschlies, & Renner, PRL 107 (2011) 081802] developed an approach to reduce the chiral extrapolation error in $a_\mu^{HVP(LO)}$
  - RBC Collaboration [Hayakawa *et al.*, PoS LAT2005 (2006) 353] developed a promising method for calculating a_μ^{HLbL} using QCD + QED lattice simulations
- Precision goals are challenging, and demand further theoretical developments as well as expected increase in computing power

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See talks in lattice-QCD g-2 sessions Monday & Tuesday 9AM

- C. Aubin: “ Hadronic vacuum polarization contribution to g-2 using staggered fermions”
- D. Renner: “Hadronic vacuum polarization contribution to g-2 using twisted-mass fermions
- T. Blum: “ Hadronic light-by-light contribution to muon g-2 from lattice QCD”

- S. Peris: “ The anomaly triangle and g-2”
- S. Cohen: “ Neutral pion to two-photon decays from lattice QCD”
- T. Izubuchi: “ New methods for lattice-QCD calculations of the hadronic light-by light contribution to g-2”

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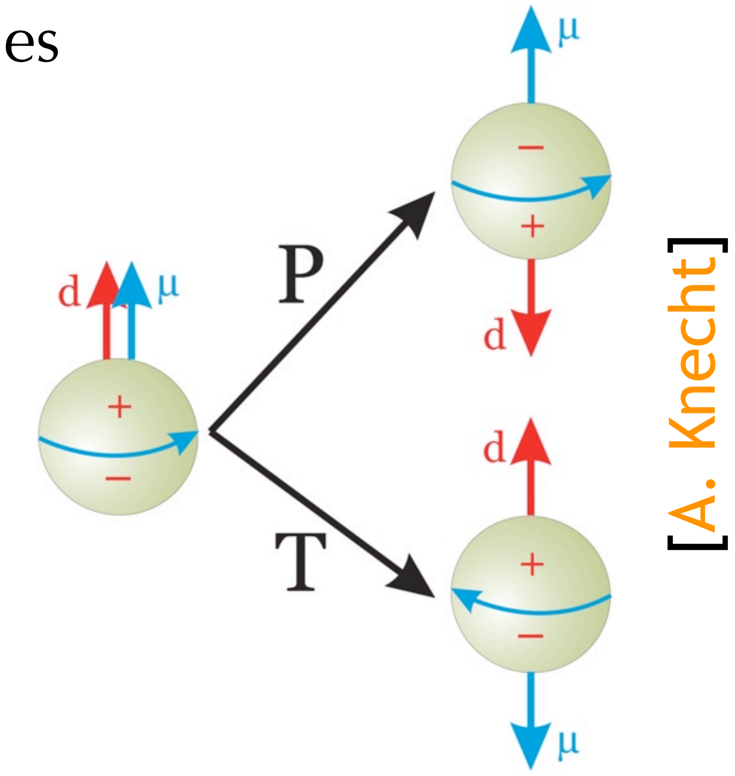
Neutron electric dipole moment



- Neutron EDM d_N violates time-reversal and parity symmetries
  - Standard-Model contribution from *CP*-odd phase in CKM matrix $d_N \sim 10^{-30}$ e•cm
  - Current experimental bound $d_N < 3 \times 10^{-26}$ e•cm
  - Contribution from QCD θ-term could in principle be larger, but experimental limit combined with theoretical estimates of d_N/θ set bounds $|\theta|<10^{-10}$
- The small size of θ ("strong CP problem") requires fine-tuning in the Standard Model or the introduction of new particle(s) and symmetr(ies)
  - **Lattice-QCD can provide first-principles calculations of the neutron EDM**
- Experimental measurement of NEDM also places strong constraints on physics beyond-the-Standard Model
  - In some cases, model predictions require hadronic matrix elements that can be provided from lattice QCD

Lattice-QCD neutron EDM calculations

✦ In the past few years progress has been made on lattice-QCD calculations of the neutron EDM using various approaches including:

(1) Directly adding a *CP*-odd term to the Lagrangian

(2) Calculating the energy difference between two spin states of the nucleon in an external electric field

✦ Current statistical errors are still ~30%, but expect calculations of d_N to ~10% in the next 5 years

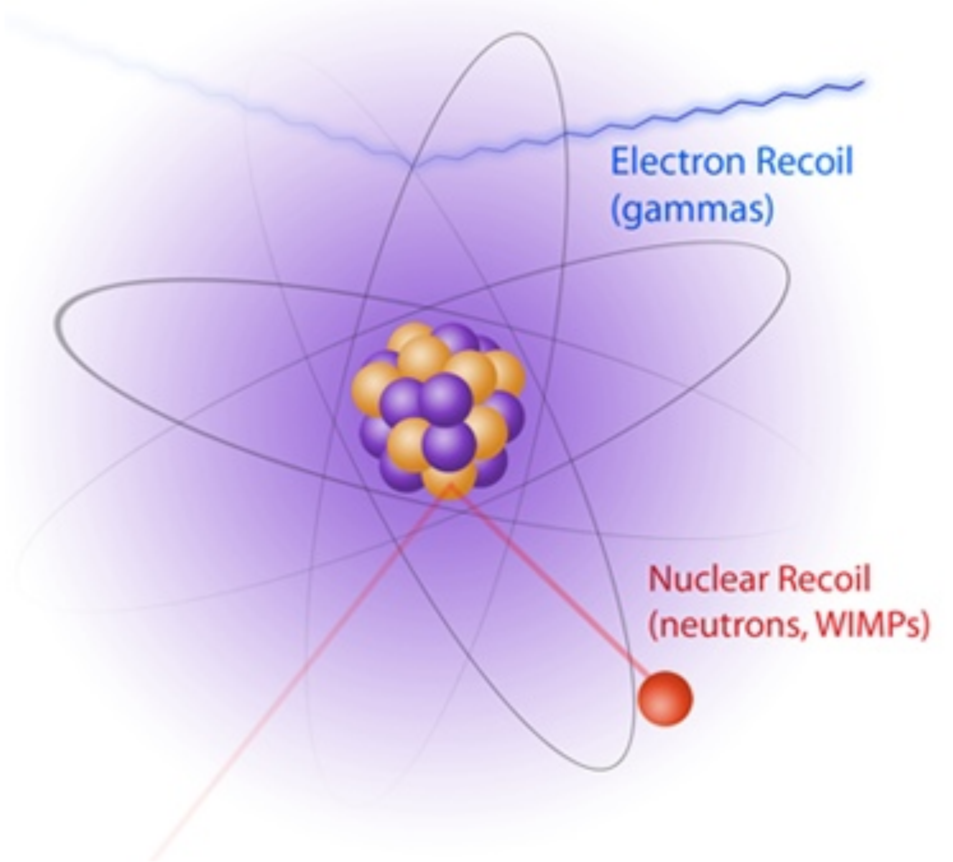
See talks in joint lattice-QCD-EDM session Saturday 11AM

- E. Mereghetti: "EDM of the nucleon and light nuclei in Chiral Effective Theory"
- E. Shintani: "Neutron EDM from Lattice QCD"
- T. Battacharya: "Neutron EDM in the Standard Model and beyond from Lattice QCD"

Nucleon matrix elements

- Nonperturbative nucleon matrix elements are quantitatively important for numerous new-physics searches, *e.g.*:

  - **Dark-matter detection:** cross-section for WIMP-nucleon scattering depends upon the light- and strange-quark contents of the nucleon



  - **Proton decay:** model predictions depend upon expectation values $<\pi, K, \eta, \ldots \,|\, \mathcal{O}_{NP} \,|p>$ of new-physics operators

  - **Neutron beta decay:** constraints on new TeV-scale interactions depend on the neutron scalar and tensor charges g_S and g_T

Status of lattice-QCD calculations

- Lattice-QCD calculation of the nucleon axial charge g_A is "gold-plated" and provides a benchmark for of the accuracy of lattice nucleon matrix element calculations
    - Present lattice uncertainty is ~10%, but increased computing power should greatly improve the precision in the next five years
- Lattice-QCD calculations other nucleon matrix elements are in earlier stages but work is ongoing

See talks in joint lattice-QCD-n-nbar oscillations session Saturday 4PM

- T. Izubuchi: "Proton Decay Matrix Elements from Lattice QCD"
- S. Cohen: "Probing TeV Physics through Lattice Neutron-Decay Matrix Elements"
- B. Plaster: "High-precision measurements of g_A and g_V in neutron decay"

- also M. Buchoff: "Lattice calculations of neutron-antineutron matrix elements" 3:15PM

Outlook for lattice QCD

Forecasts and plans

(1) Still work needed to obtain precision comparable to experiment for many quantities

- Future increases in computing power will help most sources of uncertainty, either directly or indirectly
- Improved algorithms and analysis methods being pursued, but difficult to predict

Quantity	CKM element	present expt. error	present lattice error	2014 lattice error	2020 lattice error	error from non-lattice method
f_K/f_π	V_{us}	0.2%	0.6%	0.3%	0.1%	–
$f_{K\pi}(0)$	V_{us}	0.2%	0.5%	0.2%	0.1%	1% (ChPT)
$D \to \pi\ell\nu$	V_{cd}	2.6%	10.5%	4%	1%	–
$D \to K\ell\nu$	V_{cs}	1.1%	2.5%	2%	$< 1\%$	5% (ν scatt.)
$B \to D^*\ell\nu$	V_{cb}	1.8%	1.8%	0.8%	$< 0.5\%$	$< 2\%$ (Incl. $b \to c$)
$B \to \pi\ell\nu$	V_{ub}	4.1%	8.7%	4%	2%	10% (Incl. $b \to u$)
$B \to \tau\nu$	V_{ub}	21%	6.4%	2%	$< 1\%$	–
ξ	V_{ts}/V_{td}	1.0%	2.5%	1.5%	$< 1\%$	–

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- $K \to \pi\pi$ decays ($\Delta I = 1/2$ rule and ϵ'/ϵ)
- Hadronic contributions to muon g-2

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- Electromagnetic corrections (*in progress*)
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For more details see USQCD Collaboration white papers at
http://www.usqcd.org/documents/HiIntensityFlavor.pdf
http://www.usqcd.org/documents/g-2.pdf
http://www.usqcd.org/documents/11nucleon.pdf

Summary

- Lattice QCD can **RELIABLY** compute hadronic matrix elements needed to obtain the fundamental parameters such as light-quark masses and CKM matrix elements
  - Already playing a key role in testing the Standard Model in the quark-flavor sector
  - Need to develop new methods for long-distance contributions to D-meson mixing and multi-hadron final states in $D \to \pi\pi(KK)$ decays
- Nuclear physics on the lattice is becoming mature
  - Can accurately calculate low-lying meson and baryon spectrum, and are making progress on excited states
  - Expect to obtain g_A to ~5% in the next few years, and comparable calculations of other nucleon matrix elements will soon follow
  - Ultimately aim to obtain first-principles QCD calculations of nucleon structure such as moments of quark and gluon distributions, transverse momentum distributions, and contributions to the nucleon spin
- **Calculations of the light-by-light contribution to muon g-2 are still in early stages and future errors are difficult to predict**

Outlook

- Lattice-QCD calculations will be **needed to maximize the impact of the worldwide intensity-physics program, including Project X**
    - The lattice-QCD community is now expanding our program to meet the needs of current and upcoming experiments
    - Given the expected algorithmic improvements and increase in computing power, lattice QCD will continue to systematically and steadily reduce the uncertainties in the needed hadronic parameters over the next several years
- With improved experimental and theoretical precision, precise measurements at the intensity frontier can be a powerful diagnostic tool to reveal the underlying nature of new physics discovered at the LHC or elsewhere

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We look forward to fruitful discussions with experimentalists and phenomenologists over the next several days on the role of lattice calculations for the Project X physics program.

Please come to the lattice-QCD parallel sessions!

Extras

Advertisement: latticeaverages.org and FLAG-2

- Because there are now **reliable and independent** lattice-QCD results for an increasing number of quantities relevant to flavor physics, **need averages**

(1) Laiho, Lunghi, Van de Water

- Phys.Rev. D81 (2010) 034503, www.latticeaverages.org
- Light-quark and heavy-quark quantities + unitary-triangle fits with LQCD inputs

+ (2) Flavianet Lattice Averaging Group (FLAG-1)

- Members from EU [Eur.Phys.J. C71 (2011) 1695, http://itpwiki.unibe.ch/flag/]
- Light-quark quantities only

= Flavor Lattice Averaging Group (FLAG-2)

- Members from all big US, EU, and Japanese lattice-QCD collaborations
- Light-quark and heavy-quark quantities
- **Expect first review at end of 2012**

Sensitivity to new physics

	LHT	RSc	4G	2HDM	RHMFV
$D^0 - \bar{D}^0$ (CPV)	★★★	★★★	★★	★★	
ϵ_K	★★	★★★	★★	★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	★★★
$S_{\phi K_S}$	★	★	★★		
$A_{\rm CP}\,(B \to X_s\gamma)$	★		★		
$A_{7,8}(K^*\mu^+\mu^-)$	★★	★	★★		
$B_s \to \mu^+\mu^-$	★	★	★★★	★★★	★★
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	★★★	★★★		★★
$K_L \to \pi^0\nu\bar{\nu}$	★★★	★★★	★★★		★★
$\mu \to e\gamma$	★★★	★★★	★★★		
$\tau \to \mu\gamma$	★★★	★★★	★★★		
$\mu + N \to e + N$	★★★	★★★	★★★		
d_n	★	★★★	★	★★★	
d_e	★	★★★	★	★★★	
$(g-2)_\mu$	★	★★	★		

Table 3. "DNA" of flavour physics effects for the most interesting observables in a selection of non-SUSY models. ★★★ signals large NP effects, ★★ moderate to small NP effects and ★ implies that the given model does not predict visible NP effects in that observable. Empty spaces reflect my present ignorance about the given entry.